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ELLIOT LAKE STUDY: FACTORS AFFECTING THE URANIUM MINE WORKING ENVIRONMENT PRIOR TO THE INTRODUCTION OF CURRENT VENTILATION PRACTICES

by

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SUMMARY

A study was carried out to assist in the retrospective assessment of the underground environment that existed in the Elliot Lake uranium mines in the late 1950's and early 1960's. The mining companies, Rio Algom and Denison, the miners' union, the United Steel Workers of America, the Ontario Ministry of Labour, the CANMET Elliot Lake Laboratory, the AECB Elliot Lake Office staff, the Canadian Institute for Radiation Safety, and the McMaster University Silicosis Research Group all provided cooperation and assistance to the study.

The environmental conditions and work practices of the late 1950's were established by a combination of literature review and interviews with veteran miners. Realistic time and space dependent computer models were developed to predict the concentrations, and the most critical model parameters determined.

The practices of the 1950's were imitated in a pilot raise, and extensive measurements of the radiation environment were made. Realistic values of radon and thoron daughter production and removal rates were obtained. The computer model demonstrated that it could reproduce all the observed features of the radiation environment given realistic input parameters.

The computer model was used to calculate and compare the average exposure of the miner in the 1950's with the exposure that would be expected from contemporary measurements, and with that of the miner today.

The calculated exposure is about half of that expected from contemporary measurements, which gives assurance that previous exposures for pilot raise miners were not underestimated. Relative to today's miner, the average exposure of the typical raise miner of the 1950's is estimated as three times higher for radon daughters, equal for thoron daughters, equal for exposure to gamma radiation, but much higher for uranium and quartz dust.

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RÉSUMÉ

Une étude a été menée dans le cadre de l'évaluation rétrospective de l'environnement souterrain qui existait dans les mines d'uranium d'Elliot Lake à la fin des années 1950 et au début des années 1960. Les sociétés d'exploitation minière Rio Algom et Denison, le syndicat des mineurs, les Métallurgistes unis d'Amérique, le ministère du Travail de l'Ontario, le laboratoire de CANMET d'Elliot Lake, les employés du bureau de la CCEA à Elliot Lake, l'Institut canadien de radioprotection et le "Silicosis Research Group" de l'Université McMaster ont tous prêté leur concours à l'étude.

Les conditions environnementales et les pratiques de travail vers la fin des années 1950 ont été établies à partir de la documentation existante et d'entrevues avec d'anciens mineurs. Des modèles informatiques de temps et d'espace réalistes ont été mis au point pour prévoir les concentrations et les paramètres de modèle les plus critiques ont été déterminés.

On a simulé les pratiques des années 1950 dans une aire de travail pilote et on a procédé à d'importants relevés de l'environnement radiologique afin d'obtenir des valeurs réalistes du taux de production et d'enlèvement des produits de filiation du radon et du thoron. Le modèle informatique utilisé a prouvé qu'il pouvait reproduire toutes les caractéristiques observées dans l'environnement radiologique, à partir de paramètres d'entrée réalistes.

On s'est servi du modèle informatique pour calculer l'exposition moyenne des mineurs dans les années 1950 et pour la comparer, d'une part, avec l'exposition à laquelle on aurait pu s'attendre d'après les relevés de l'époque et, d'autre part, avec celle des mineurs aujourd'hui.

L'exposition calculée équivaut environ à la moitié de celle prévue d'après les relevés de l'époque et confirme ainsi le fait que les expositions antérieures des mineurs de ce type n'ont pas été sous-estimées. Par rapport aux mineurs actuels, on estime que l'exposition moyenne de ces mineurs dans les années 1950 est trois fois supérieure pour les produits de filiation du radon, est égale pour les produits de filiation du thoron, est égale pour les expositions aux rayons gamma, mais est très supérieure pour les poussières d'uranium et de quartz.

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1. INTRODUCTION

This study was carried out on behalf of the Atomic Energy Control Board, under Contract No. OSQ83-00094, DSS File No. 14SQ.87055-3-4024, by DSMA ATCON LTD. The purpose of the project was generally to evaluate the radiological hazards associated with the uranium mine working environment prior to the development and adoption of modern ventilation practices.

Evaluation of those early conditions is now difficult because of the limited number of measurements made at the time, and the measurement methods used. This study was carried out to construct and verify a realistic computer model of the working environment of that time, and to generally enhance the knowledge of the key variables affecting the radiation environment in the late 1950's in the mines at Elliot Lake.

The scope of work for this study was developed by joint consultation and agreement between representatives of the Atomic Energy Control Board, the Denison and Rio Algom uranium mining companies, and the Elliot Lake union locals of the United Steel Workers of America.

The specific tasks to be accomplished were:

(1) Establishment of 1950's parameters -
   (a) review and compile pertinent background data from contemporary file records and other sources of information.

   (b) Evaluate the responses from interviews of veteran workers as to environmental conditions and work practices existing at that time.

(2) Construct a computer model of a realistic working situation, using the data collected above and other information, and determine the most critical parameters.

(3) Create in an operational underground uranium mine a representative working situation, make measurements of the radiation environment, and test the validity of the mathematical model by comparing its predictions against the measurements.

(4) Develop estimates of the range of radon daughter concentrations that may have existed in the work place.

(5) Estimate confidence limits in the assessment of radiation conditions associated with such a work environment in the past.

(6) In addition to the specific objective of this study (model testing), measure additional parameters - e.g. thoron daughters, gamma ray exposure rates, dust concentrations, particle sizes and solubility to provide additional understanding of the total radiation environment.

This study was carried out with the cooperation and assistance of the mining companies, Rio Algom and Denison, and the union, the United Steel Workers of America. Members of the AECB Elliot Lake office staff provided field assistance. Observers from the mines, the union and the AECB were present during the field trials.

The participation of other agencies and research groups in this study was solicited. The McMaster University Silicosis Research Group actively participated, sending a team member with dust measurement equipment. The Ontario Ministry of Labour provided an observer, and loaned a portable scaler/counter, a condensation nucleii counter, and a gas chromatograph for tracer gas measurements. The CANMET Laboratory at Elliot Lake provided calibration facilities. The Canadian Institute for Radiation Safety (Elliot Lake) provided CAE personal dosimeters. The cooperation of all these groups is gratefully acknowledged.

2. PROGRAM ORGANIZATION

The program was carried out in 4 phases. The first phase was information gathering. A review was carried out of internal uranium mine reports and published information on mining practices at that time in both uranium and other mines. Interviews were also held with miners who had worked in Elliot Lake in the late 1950's to obtain their recollections of the mining conditions and practices. Information from all these sources was combined to estimate the nominal work, ventilation, and dust control practices in Elliot Lake in the late 1950's. The results of this phase are included as Appendix 1 to this report.

The second phase was a modelling program. A general computer model was developed to predict radon and thoron gas and their daughter concentrations in the mine environment for both steady state and variable conditions. The purpose of this model was to generalize the results of the experimental study, and to simulate the effect of changes in mining practices on concentrations. The model was tested for accuracy and reliability by comparing its predictions with the published results of similar, but less general, models. Agreement was excellent. The model and the solution methods are discussed in detail in Appendix 2, together with examples of the output.

The third phase was the underground experimental study, in which the mining methods and ventilation and dust control practices of the late 1950's were imitated while measurements were made of the radiation environment. The instrument calibration procedures are given in Appendix 3.

The fourth phase consisted of two steps. First, realistic values of production and removal parameters for radon and thoron daughters, and dust were calculated from the concentrations observed during the experimental phase. Second, these parameter values were used in the computer model to simulate the changes in concentration with mining conditions, and to compare the exposure to miners in the late 1950's with that of today.

A solubility in simulated lung fluid study was carried out on collected airborne dust samples and is reported on in Appendix 4.

Ventilation rates were measured by tracer gas techniques. The method used is described in Appendix 5.

A bibliography is included in Appendix 8.

3. SELECTION OF COMPUTER MODEL

A general treatment of the radionuclide growth with time in air requires solutions of two sets of simultaneous differential equations. The first set of 8 equations describes the supply and removal rates of radon, the free and attached form of each of its three daughters, and of the aerosol concentrations in the area. The second set of six equations describes the supply and removal rates of thoron, its two longer lived daughters and the aerosol concentrations in the area. This approach was first suggested by Jacobi (Ja 72) and Porstendorfer (Po 78). The original equations were extended by Robertson (Ro 81) who added the aerosol term. Solution of these equations is impractical without the use of a computer.

Schroeder and Evans (Sc 69) simplified the problem for radon daughters in mine air by assuming that the aerosol concentration was high enough that essentially all daughters were attached, and that radioactive decay was the major removal mechanism. Under these circumstances the standard Bateman equations apply and the growth of WL with time in initially pure radon can be approximated by a power law. This approach has been generally successful, and with modifications has been the basis of several models since e.g. Beckman (Be 79), Bigu (Bi 81) and Notely (No 83, No 84). However, for this experimental program, it was felt that the assumptions of the Schroeder model were too limiting, and so the computer model was based instead on the direct solution of the simultaneous equations. This would give the individual radon and thoron daughter concentrations in addition to the WL, so that daughter ratios as well as WL could be compared with measurements.

Two programs were written. The first, "MINES", was to calculate the in steady state concentrations from place to place in a tunnel network. The validity of this model was checked by setting the daughter removal rates to zero, and comparing the WL predictions with the Schroeder model. Agreement was exact. The second program, "TRAISE" was to calculate the time variation of concentrations at a single place - the head of the raise. The validity of this model was also checked by setting the radon supply rate constant, the daughter removal rates to zero, and comparing the WL growth to the Schroeder model. Agreement was exact. The models and the solution techniques are described in detail in Appendix 2.

The sensitivity of the predictions of radon and thoron daughter concentrations given by the models MINES and TRAISE was determined during the planning phase for the experimental program by running a number of cases with input parameters based on the information obtained in the information gathering phase. These showed that the parameters of greatest influence on WL were the supply rate of radon, thoron and daughters in the work space via ventilation air, the release of radon and thoron from surfaces, the amount of compressed air released during a task, and the nature of the air flow patterns in the work place, which determine the effective volume that is ventilated. Other parameters, such as the attachment rate, unattached fraction and surface deposition rates were found to be of minor importance to the model as long as the attachment rate

was high.

The radon supply rate via ventilation air, the amount of compressed air released, and the ventilation pattern in the work space are highly site specific, and therefore a well controlled experimental site would be required to create a work situation to generate data of high enough reliability to test the validity of the mathematical model. The site of choice was therefore a blind end tunnel, with small cross-sectional area to maximize the effect of ventilation changes.

4. SELECTION OF EXPERIMENTAL SITE

4.1 Historical Review

The ore body at Elliot Lake is a placer pebble conglomerate deposit 2 to 10m in thickness, and extends over many km². The deposit was discovered in 1953, and by the end of 1956 there were 5 mines being prepared for production. In 1959 there were 10 mines in operation with peak total employment of 10,000 persons, 5,000 of which worked underground. With such a large ore body there were significant variations in the ore thickness and footwall contours from mine to mine, and a corresponding variation in mining methods. Where the ore thickness exceeded 3.5m with moderate slopes (10 degrees) over large areas, trackless mining was used. Haulage ways were driven on the strike of the ore body, and rooms were turned off up dip at regular intervals in a room and pillar pattern. Broken ore was removed by diesel or electric haulage vehicles to the shaft or to conveyor belts. Three mines used this method exclusively.

In those areas where the ore was less than 3.5m thick, or slopes steeper, scraper stopes were used, with loading into tracked or trackless vehicles. Typically, drifts were driven across the ore body on the strike separated by about 80m on the dip. At 50m intervals twin pilot raises separated by a 4-8m pillar were driven up-dip from drift to drift, and then enlarged sideways into stopes up to 20m wide. Broken ore was removed from pilots and stopes by cable operated scrapers (slushers) with the winch located on a bench off the lower drift, either directly into tracked or trackless vehicles, or into box holes giving access to tracked footwall haulage by diesel or electric locomotives. Three mines used tracked haulage exclusively, and the remaining four used both track and trackless haulage, depending on the areas of the mine.

As the mines expanded on both strike and dip, the ventilation system became more complex, and the potential for zone or regional air recirculation became greater. As recirculated air has higher radon and radon daughter concentrations, the radiation levels measured at any place in a mine depends not only on the radon released in the working place, but also on how well local recirculation was controlled, and the degree to which fresh air was kept separate from exhaust air.

The variability of radiation levels with ventilation conditions, and the wide variety of mining tasks and methods in use in the 1950's make it impracticable to simulate the conditions in a mine as a whole. The goal of the experimental program was therefore more modest - the recreation of a specific mining practice of the time under controlled conditions. Phase 1 of this study (information gathering) found that there were basically 3 working environments - pilot raises, drifts, and stopes. The reported radiation and dust levels for each was similar, but the Morrison Committee (Mo 59) in reviewing working conditions at Elliot Lake in the late 1950's, had suggested that the worst working environment was to be found in the driving of up-dip pilot raises in stope preparation work. At that time, the only ventilation in raises was the compressed air released from the miner's drills, or from air

valves left 'cracked open'. Auxiliary ventilation and 'flow through' ventilation was used in the drifts and stopes. The Committee recommended positive auxiliary ventilation for pilot raises in the belief that it was required "if the maximum allowable concentration of silica dust and radon daughters are not to be exceeded throughout the raise". This belief in the combination of high dust and radiation levels in pilot raises was confirmed by the Phase 1 study, and so a pilot raise was the experimental location of first choice.

4.2 Site Selection Criteria

As the experimental work would be carried out in an operating mine, the choice of site was circumscribed by the general requirements that it should be remote from routine mining operations to avoid mutual interferences, and that conditions in the area should be controllable. Despite the mechanization that has taken place in the mines since the 1950's, the pilot raise/stope development routine still accounts for nearly 50% of production at one of the mines. Although most of those sites did not meet the criteria above, there was a location in the Rio Algom Quirke II mine, where a pilot raise was being driven up-dip for stope development. Drilling was carried out with jackleg drills, and broken ore was removed by slushing. This operation was similar to that carried out in the 1950's except that an auxiliary ventilation system was provided, and modern dust control practices were in use. The site was located on a main airway, and was remote from other mining operations.

This was an ideal site for an experimental study. The practices of the 1950's could be imitated easily by turning off the auxiliary ventilation, and the site was remote and the scale of work was small (2 miners), so that there would be minimal interference with other mining operations and production goals of the mine as a whole. Through the kindness of Rio Algom management, this site (736 Raise) and the miners were made available for a two week period in February.

4.3 Site Description

A sketch of the 736 raise is shown in Figure 1. Twin pilot raises of 2.5m x 2.5m cross-section were being driven up-dip from an approximately circular cut-out on the north side of a main airway. The slusher winch is located in the eastern half of the cut-out, on a wooden platform raised about 5m above the main airway floor, and reached by a ladder. The hanging wall of the cut-out and the raises is the 'barren' quartzite that overlays the ore, but all other rock surfaces are ore, averaging 0.125% in this area. Access to the East raise was via a foot- board from the slusher bench, and access to the West raise was via a ladder from the floor of the cutout. A sketch of the auxiliary ventilation layout is shown in Figure 2, together with the air circulation pattern in the cut-out.

The ventilation system consisted of two 48cm (19") diameter electric axial fans placed in series, hung from the roof of the main airway, and discharging into 48cm diameter rigid fibreglass ducting which ran to a 'y'

junction with 30m diameter flexihose beside the slusher bench. One branch ran straight to the West raise, the second branch passed across the front of the slusher bench and then turned through a right angle to reach the East raise. A 10cm diameter vent was provided in one leg of the 'y' to ventilate the slusher bench but the damper was kept closed for the experimental period. Inside each raise the air was carried in 30cm diameter rigid fibreglass ducts. The ventilation discharge rates at the start of the experimental program were 420L/s (900cfm) in the West raise, and 160L/s (350cfm) in the East raise.

4.4 Comment

This site was not identical to the standard site of the 1950's. At that time, the slusher bench was reached via a strike drift of much smaller cross-section and greater length than this cut-out.

5. MEASUREMENT PROGRAM

The intention of the measurement program was to measure the concentrations of radon, thoron and daughters released during the mining cycle, and the effect on these produced by various forms of ventilation. Additional measurements were also made to assist in deriving parameters for the computer model, and in quantifying the radiation environment. As part of a co-operative program a representative of the McMaster Silicosis Research Group made konimeter and gravimetric dust measurements during the program to assist their interpretation of historical konimeter dust measurements. The calibration of all radiation measurement equipment was cheched at the CANMET Laboratory, as described in Appendix 3.

5.1 Airborne Radioactivity Measurements

The frequency distribution of radon and thoron daughter measurements was analyzed by location and experimental conditions.

Airway

The distribution of all airway measurements was log-normal, the median values (geometric mean) and geometric standard deviations (GSD) were GM=0.115WL(Rn) GSD=1.12; GM=0.125WL(Tn) GSD=1.2.

Auxiliary Ventilation in Operation

Face - the distribution of all measurements was log-normal with GM=0.08WL(Rn), GSD=1.75; and GM=0.125WL(Tn), GSD=1.4.

The mean values are lower than the mean value in the airway from which the ventilation air was drawn, and they are more variable. This is the result of the additional local ventilation produced by the release of compressed air during drilling reducing the WL.

Slusher Bench - the distribution of measurements was log-normal, with GM=0.08WL(Rn), GSD=1.75; and GM=0.125WL(Tn), GSD=1.4.

Compressed Air Ventilation

Face - the distribution of all measurements was approximately log-normal with GM=0.33WL(Rn), GSD=9.0, and GM=0.11WL(Tn), GSD=2.7. This high variability reflects the variability in the amount of air released when compressed air was the sole ventilation. When the air was turned off, overnight concentrations were 6-10WL(Rn), 0.5WL(Tn), but during drilling with additional compressed air used to improve visibility, concentrations fell to less than 0.05WL(Rn), 0.05WL(Tn).

Slusher Bench - the distribution of measurements was nearly log-normal, with GM=0.35WL(Rn), GSD=1.6; GM=0.165WL(Tn), GSD=1.6. These values are higher and more variable than those when the auxiliary ventilation is in operation, the result of higher WL's in the air leaving the

raises when compressed air was used, and circulation of this air over the slusher bench.

5.2 Comments

The radon and daughter concentration in the fresh air supply were fairly constant throughout the experimental period. Daughter ratios (A:B:C) were typically 1:0.6:0.5. The ThB concentration was close to 1.0pCi/L, with ThC at about 50% of equilibrium, for thoron WL's approximately equal to the radon WL.

The radon and daughter concentrations at the slusher bench were consistently greater than those measured in the fresh air supply. This is the result of local recirculation in the cut-out of radon leaving the raises and emanating from the broken ore on the floor.

The auxiliary ventilation holds concentrations at the face only slightly higher than the concentrations measured in the fresh air supply, even when the effectiveness was reduced by increasing the distance between the end of the duct and the face to beyond the regulation maximum of 7.5m (Ri 80). Concentrations were in the range of 0.1 to 0.2WL.

When drill air plus up to 50L/s of compressed air was used for ventilation, the maximum ventilation rate at the face was comparable to that of the auxiliary ventilation system operating at large duct to face distances, but concentrations were in the region of 30pCi/L and 0.05WL with average daughter ratios of 1:0.4:0.3. This marked disequilibrium is the result of the relatively large amounts of radon free air released during drilling and the short residence time of the air at the face. Visibility was very poor when the drill air was the only source of ventilation. The addition of a small amount of compressed air made a significant improvement by dispersing the fog into a larger volume, and providing additional dilution air. Radon daughter concentrations did not seem to be greatly affected by this additional air.

When ventilation was by compressed air with the valve "cracked" open, concentrations in the region of 0.3WL were obtained. The air released at the face took approximately 30 minutes to travel down the raise, and radon and daughter concentrations increased to 0.6 to 0.7WL near the mouth.

When the raise was left with no ventilation, concentrations increased at the rate of about 0.5WL/h, and so the concentrations met with during scaling, after slushing without ventilation were in the range of 0.5-1.0WL. The daughter ratios averaged 1:0.6:0.4.

The natural ventilation in the raise limited the maximum concentrations reached in the raise over an 18 hour period without additional ventilation to 1000 to 1400pCi/L radon and 7 to 9WL.

5.3 Illustrations

Different ventilation methods produced different air circulation patterns in the raise. Sketches of these patterns are shown in Figure 3. The radon and daughter concentrations measured at the raise head in the vicinity of the miner and their probable variation with time are shown in Figure 4. The mining activity is also shown, together with the WL(R) at the slusher bench for comparison.

6. ADDITIONAL MEASUREMENTS

6.1 External Radiation Measurements

External radiation measurements were made with a 5 channel scintillometer, an Eberline PRM-7 scintillation exposure rate meter, and self-reading condenser chambers. The readings are shown in Table 1.

Photon flux measurements were made with a 5 channel scintillometer. The fraction of counts due directly to thorium relative to those from uranium varies from 0.18 to 0.42, approximately reflecting their average activity ratios in the ore. As the exposure rate per pCi of thorium is 50% higher than that for uranium, changes in the Th/U ratio have a significant impact on any correlation of exposure rate with ore grade.

Most scattered photons have energies less than 400keV, so changes in the ratio of scattered to direct radiation are reflected by changes in the ratio of 80keV/ 400keV counts on the scintillometer. This ratio changes from 4.2 in the confined quarters of the raise to 5.2 in the open spaces of the airway.

Simple scintillation exposure rate meters such as the PRM-7 detect all photons over about 200keV with nearly equal efficiency, but the exposure per photon increases by a factor of 8 between 200keV (the energy of scattered photons) and 1.6MeV, the energy of direct photons from U and Th. Changes in the percentage of scattered photons therefore change the meter reading by more than the exposure rate. As a result of the higher scatter in the mine environment, the PRM-7 is estimated to read 20-30% higher than at the surface for the same exposure rate.

Self-reading condenser chambers were exposed for 48 hours, and indicated exposure rates of 1-2mR/h in the raise. These chambers have flat response to photons above 80keV, and indicate 'true' exposure rates of about 75% of those shown by the PRM-7, showing the influence of scatter on scintillation meter readings.

It had been intended to use a Victoreen 440 exposure-rate meter to measure the total exposure rate from both direct and scattered photons, and to estimate the dose-rate from beta particles, but the electronics failed before any measurements could be made. No measurements were made of the dose rate from beta particles.

6.2 Unattached Fraction

The fraction of RaA unattached to aerosol particles was estimated by measuring the activity collected on 120 mesh copper screen placed in front of a filter in the standard 25mm holder.

The product of collection and front face counting efficiency for unattached daughters at a nominal face velocity of 16cm/s was calculated to be 0.23. The collection efficiency for attached daughters was estimated

empirically. The concentrations of RaC (100% attached) calculated from the screen using an efficiency of 0.23 averaged 2.5% of those measured by the filter. The concentrations of RaA measured by the screen was corrected for collection of attached RaA by subtracting 2.5% of the RaA concentrations measured by the filter. The remainder is assumed to be the concentration of unattached RaA. This correction procedure is adequate for the low unattached daughter fractions found in this study. The values of unattached fraction are given in Table 2.

The accuracy of the measurements is generally low, for only small amounts of activity were collected on the screen. The activity on two screens was too low to calculate concentrations.

The unattached fraction in mine air was less than 3% at the start of the program, but two values in the region of 6% were obtained on March 1st. When compressed air alone was used for ventilation, unattached fractions were 3-7%, suggesting that it was relatively clean, but the air released while drilling had essentially all daughters attached.

The mine intake air is heated by direct fired propane heaters, so the concentration of condensation nuclei (and hence the attachment rate) in that air would be expected to be higher than in the compressed air which is supplied by surface compressors. A condensation nuclei counter was lent by the Ontario Ministry of Labour for this study, but unfortunately the electronics did not survive the trip. Direct measurement of condensation nuclei concentration could not be made.

6.3 Deposition Velocity

The rate at which radon and thoron daughters deposit on surfaces is expressed as deposition velocity, defined as:

$$V = \frac{\text{daughter surface deposition rate}}{\text{daughter concentration in air}}$$

The deposition velocity of those daughters that are free - not attached to aerosol particles (V_f) - is much higher than that of attached daughters (V_a), so the total deposition velocity depends largely on the fraction of the daughter that is free. In the surface environment V_f is in the range of 0.1-0.5cm/s, depending on air velocity (Sc 83).

The total deposition velocity of radon daughters was measured by two methods. The first had been used for measurements in houses (Sc 83), in which 10cm diameter paper discs were exposed for 2 hours and then counted in contact with a 12cm diameter alpha scintillator. This proved unsatisfactory underground, for the 20-30pCi/L radon concentrations present in the large volume counter chamber deposited daughters on the scintillator, and the background count rate increased steadily with time. Final backgrounds were greater than the activities on the discs, and estimates could not be obtained.

The second method used 7x7cm squares of zinc sulphide scintillation paper, which was exposed for 2 hours, and then counted with the scintillator side in contact with a bare photomultiplier tube. Daughters produced by the radon in the counter could not reach the scintillator surface, and the background was constant.

Multiple counts were made over a period of 30 minutes, and the deposition rate of each daughter was calculated by a least squares routine. This procedure does not require that the collector reach radioactive equilibrium with the air. In most cases, so little activity had deposited that significant estimates of RaB and RaC deposition rates could not be obtained. These cases were analyzed on the basis that only RaA was deposited.

The surface activities and the equivalent maximum deposition velocity of RaA are shown in Table 3.

The total deposition velocity of RaA (V_T) ranged from $1-10x10^{-2}$cm/s. Given the low unattached fractions present in the mine environment, this implies free RaA deposition rates of 0.5 to 1.0cm/s, which is higher than the values generally found in the surface environment. This may be a reflection of generally higher air velocities over mine surfaces.

6.4 Long Lived Airborne Activity

A number of standard 28 litre air samples taken at times of high dust production were counted at intervals over a period of several days to determine if there was a large amount of long lived activity present other than ThB. None was detected. Some longer duration samples were taken at times of expected high dust concentrations, but the ThB activity present even after several days decay gave a detection limit of 0.05pCi/L and the dust concentrations were all less than the detection limit. As dust activity concentrations were too low to affect the accuracy of radon and thoron daughter measurements, the standard air samples were all analyzed on the basis that the activity on the filter from long lived material was neglible.

6.5 Dust Solubility

"Respirable" dust for solubility analysis was collected on 37mm 0.8um cassette filters preceeded by a 10mm nylon cyclone opening at 1.7L/m. The cyclone and flow controlled battery pump were lent by the McMaster Silicosis Research Group. Samples were collected over the entire shift in the raises during slushing and drilling and also at the slusher bench. The cassettes were sent to CRNL for analysis.

The mass of respirable dust collected was low, as shown by the clean appearance of the filters, so total airborne dust samples were collected at the slusher bench on open face 37mm 0.8um cassette filters at a flow rate of 25L/m provided by an electric pump. Each sample was over at least a 20 minute period, for a collection volume of at least $0.5m^3$ Filters were changed only when there was a visible surface deposit. The cassettes were also sent to CRNL for analysis.

The masses of respirable and total dust collected were surprisingly low, and contained only about 3mg of uranium ore dust. A full "solubility in lung fluid" analysis requires 100mg of uranium ore dust, so a modified analysis was carried out on all dust collected to provide an upper bound estimate of solubility. Approximately 30% of the dust was Class D soluble. The CRNL report on the study is included as Appendix 4.

6.6 Thoron Measurements

Estimates of thoron daughter concentrations were made from most air filter samples. The thoron WL was generally comparable to the radon WL in the ventilation air, the slusher bench air, and at the face when the auxiliary ventilation was operating. Even when ventilation was provided by drill air alone, WL(T) was still approximately equal to WL(Rn).

The value of WL(T)/WL(Rn) differs from unity only at lower ventilation rates, and that is because WL(Rn) increases faster than WL(T). Overnight ventilation with the compressed air valve cracked open gave WL(Rn) of about 0.6WL, but WL(T) increased only to about 0.2WL for a ratio of 0.3. When the raise was left overnight without ventilation, WL(Rn) rose to 6-8WL, but WL(T) rose only to 0.3-0.7WL, for a ratio of 0.1.

The apparent lack of sensitivity of WL(T) to ventilation rate is a result of the long half life of ThB compared to radon daughters. At ventilation rates too low to disturb the equilibrium of radon and its daughters (0.2h/ac) thoron and ThB are already severely disequilibrated. Higher ventilation rates significantly decrease the equilibrium of radon daughters, but the effect on the already disequilibriated ThB is much smaller.

6.7 Pylon Measurements

A Pylon WLM-1000C automatic 3 channel alpha spectrometer and pump was made available by the AECB, Elliot Lake. A measurement cycle of 30 minutes is possible with this instrument, with estimates of both radon and thoron daughter concentrations and WL's. The batteries were not in good enough conditions to operate the instrument for more than an hour at mine temperatures, and the unit was too large and heavy to move about conveniently, therefore it was installed at the slusher bench where it ran on AC power. The measurements were comparable to the concentrations measured at the slusher bench by the standard filter method.

6.8 Relative Humidity

The relative humidity of the mine air was measured with a sling psychrometer, graduated in 0.5°C increments. The readings and the humidity are shown in Table 4.

The ventilation air to the mine is heated to a little above 0°C to prevent freezing. Rock temperatures increase slowly with depth at Elliot Lake, and

the 736 raise was only at 450m depth, so the heat input from the walls was small. The road bed of the main airways is made of crushed rock, and is wetted each shift to prevent the resuspension of dust by vehicles. Water is sprayed into the air to help keep the road bed damp, and at ore dump points. As a result, the mine air was cool (10°C) and at about 85% saturation.

A few measurements were made in the work zone while drilling with compressed air ventilation. The air was cooler, as a result of the expansion of the compressed air, and very close to saturation, due to the release of water fog by the drill. The compressed air itself was sufficiently dry not to produce any visible fog when it was allowed to expand through a small orifice.

6.9 Ventilation Rate

The rate at which contaminants are removed from a space was measured directly by releasing SF_6 tracer gas in the space and measuring the decrease in concentration with time as described in Appendix 5. This method avoids the need to measure both the input ventilation air flow and the volume of the ventilated space.

Face

The ventilation period with the auxiliary ventilation system in operation at 7m from the face was 1min/ac. When the distance was increased to 17m, the period was 6 to 7min/ac. In this case the additional air added by the drill significantly decreased the ventilation period to 4min/ac when drilling was continuous.

When the air valve on the compressed air line was opened to provide air for ventilation, periods of 6-11min/ac were measured, depending on the valve opening. Visibility was so poor when just the drill exhaust air was used for ventilation the miners cracked open the air line to help disperse the drill fog. The periods measured under these conditions varied from 7-11min/ac, depending on what fraction of time the drill was running and the airline valve opening.

The movement of the slusher bucket up and down the raise causes some air movement and ventilates the face even if there is no other forced ventilation. The period was measured once at 2h/ac.

Slusher Bench

When the auxiliary ventilation was operational, the slusher bench was ventilated by the air leaving the raises in addition to that circulating in the cut-out. The period was about 5min/ac. When compressed air alone was used for ventilation, the ventilation was mainly by cut-out circulation and the period increased to 20min/ac. The slusher bench/cut-out arrangement for this site differs from that in use in the 1950's, so these values may not be representative of the slusher bench ventilation rates that existed then.

7. DUST MEASUREMENTS

7.1 Measurement Methods

The miners' work area was sampled every 15 minutes by taking 3 konimeter "snaps" in rapid succession. Each "snap" impacts the dust contained in 5cm³ air against a greased plate. The collected dust is treated with acid, and heated to remove soluble and combustible dusts, and then the number of particles present on the plate is counted optically. The size range of particles collected and counted is approximately 0.2-5.0um.

The konimeter count is believed to be related to the quartz concentration in the work area, and has been used as a workplace dust control indicator in Canadian mines for 50 years. The maximum dust concentration measurable is approximately 1000 particles per cm³(ppcc), the minimum concentration reported is 50ppcc.

The miners also wore a constant flow pump operating at 1.7L/m, and a 25mm filter cassette preceeded by a 10mm nylon cyclone to remove 'non-respirable' particles. The filters were changed at intervals to estimate task dust exposures. Total dust was determined gravimetrically, and analyzed by infrared spectrometry to determine quartz. Four members of the investigation team wore CAE integrating alpha dosimeters for the last 4 days of the experiments. The filters were weighed to estimate total dust exposure.

7.2 Gravimetric Measurements

The gravimetric measurements did not directly reflect the konimeter counts. Only those activities that gave the highest konimeter counts generally gave detectable quartz, but there were too few gravimetric measurements to draw any firm conclusions.

As uranium ore dust is 30 to 50% quartz (On 74), the low quartz concentrations suggest that most of the material collected on the filter was not uranium ore dust. This is supported by the soluble dust study (Appendix 4), the analysis of dust on CAE dosimeter filters (Section 7.6), and the observation that there was often visible staining on the routine air-filter samples even at times of low ore dust production locally.

The additional material may be drill oil droplets, rust particles from the compressed air lines, ANFO explosive fragments released during loading, powder smoke, and exhaust particles from diesel equipment that operated in the airway at intervals through the day. The presence of large amounts of inactive dust would explain the poor correlation between simple gravimetric measurements and konimeter counts (mineral dusts).

7.3 Results

Each konimeter measurement reported in Table 8 is the mean of 3 "snaps" separated by 20-30 seconds. Figure 5 shows the results

graphically.

7.4 Discussion

The first hour of drilling is a period of intense dust production, as shown by the konimeter measurements of >1000ppcc. This is because the driller starts most of his holes by drilling them to a depth of a few centimeters (collaring) during this period, and spends the rest of the shift deepening them in succession.

The water released from the drill bit is least effective in trapping the rock dust when the bit is on the surface of the rock, and so the dust release is greatest during this phase. Once the bit is well into the hole, the water is able to trap almost all of the dust produced, as shown by konimeter counts of 50ppcc after the collaring dust had cleared away.

These modern drills and bits suppress dust release during drilling four times more effectively than the drills that were in use in the late 1950's. At that time Yourt (Yo 55) measured dust concentrations produced by new drills and bits in a similar situation with drill exhaust air as the only ventilation, and obtained konimeter counts averaging 200ppcc. The dust exposure from drilling (as opposed to collaring) is low, amounting to less than 200ppcc.h for the five hours drilling with modern drills. For 1950's drills, the exposure would be 1000ppcc.h. These improvements in dust control may not have reduced the dust release during collaring, so the dust released per hole today may be similar to that released in the 1950's. If that is the case, the ratio of the collaring dust exposures can be estimated from the work place ventilation rates.

The modern miner works with an auxiliary ventilation system which gives a ventilation period of about 1 min/ac. When drill air is the only ventilation, the ventilation period is 10 min/ac or longer. Appendix 6 shows that the ratios of the collaring dust exposures (1950: today) can be as high as 20:1. The presence of dust in other stages of the mining cycle means that the ratio of shift exposures will be lower than this, but the observed ratios of konimeter counts show that the 1950's raise miner could easily experience dust exposures 10 times higher than today.

These estimates are higher than previous estimates based on mine average dust counts, e.g. Appendix A, and Ham Commission (Ha 76). This is not surprising, for these measurements were made adjacent to the driller, and concentrations are always highest at the source. Mine average counts may provide a good indication of the success of dust control measures, but they cannot provide good estimates of the individual dust exposures of drillers who are at the dust source.

7.5 Correlation of Dust and Radon Daughter Concentrations

It seems to have been generally believed in the 1950's that high levels of dust and airborne radiation occurred together, e.g. (Mo 60 ibid). The radon daughter and konimeter readings made during the program showed that there was in fact very little correlation, as would be expected for the sources of radon and dust are independent. Figure 6 shows the simultaneous variations in WL and dust on one day when there was a major change in the dust production rate caused by a decrease in water pressure. There was no corresponding increase in the measured WL.

7.6 CAE Dosimeters

The dust collected on the filters of the CAE dosimeters was analyzed gravimetrically by the Canadian Institute for Radiation Safety. One team member spent most of their time on the slusher bench operating counting equipment in mine air and their 4-day average dust exposure was 0.1mg/m³.

The other team members spent much of their time in the raises, and their 4-day average dust exposures were 4.5mg/m³, 3.4mg/m³, and 3.9mg/m³. The driller's dust exposure would be higher than this.

7.7 Long Lived Active Dust

The detection limit for LLD with the sampling and counting procedures used was about 0.05pCi/L.

The DAC for uranium ore dust is about 0.02pCi/L (0.8Bq/m³, so long lived dusts could not be detected at the DAC. However, as measured concentrations did not exceed the detection limit (3 DAC), even when drill air was the sole ventilation, we can be reasonably certain that exposure to the drillers did not exceed 3 DAC.

This is generally confirmed by the average long lived dust activity collected on the CAE dosimeters, which was 0.07Bq/m³ (mine air), and 0.19, 0.32, 0.38Bq/m³ for the team members who spent time in the raises. The only ventilation used in this period was drill air and compressed air, and conditions were similar to the 1950's. This suggests that average LLD concentrations even then may not have been higher than a few DAC.

8. DERIVATION OF PARAMETERS FOR COMPUTER MODELLING

8.1 Radon Release Rate from Surfaces

The computer models require as input the average radon release rate per m² of surface, which is used to compute the radon input per unit length of the tunnel.

The average radon release rate per m² of the raise surface was estimated from 9 measurements of the change in radon concentration in travelling between two sample locations separated by 26m. Auxiliary ventilation was in use for 3 of the measurements, compressed air and drill air was the ventilation for the other 6 measurements. They gave total radon release rates lying between 4,000 - 6,000pCi/s, with the lower value more probable. For a raise with nominal dimensions of 2.15m x 2.2m this was released from 226m² for an areal release rate of 1,000 - 1,500pCi/min/m². The accuracy of these values depends mainly on the accuracy ventilation were high enough to measure with an anemometer, are good to 15%, whereas the velocities with compressed air ventilatin were estimated from smoke puff travel measurements, and are good to no better than 30%.

A second independent estimate was obtained from the rate of radon concentration increase with time when ventilation was cut off. The mean rate of increase at the head of a clean raise was 1.48pCi/min/L. For a raise with a nominal dimension of 2.15x2.2m, this is equivalent to an average radon release rate of 800pCi/min/m². The radon concentration did not rise linearly with time in these tests, indicating that there was still some air movement in the raise. This value may be an underestimate. More frequent measurements over a longer accumulation period would be needed to get an idea of the uncertainty produced by these conventional fluctuations.

Given the uncertainties in these estimates, a reasonable estimate of the average radon production rate averaged over the entire raise surface is about 1,000pCi/min/m².

We know that all the surfaces do not release radon at equal rates. The "typical" release rate for ore is 660pCi/min/m² (De 83), and the hanging wall was "inactive" quartzite with a "typical" release rate of 70pCi/min/m² (De 83), which suggests that 60% of the radon released into the raise comes from the layer of broken ore that covers the foot wall. This would give a release rate from broken ore of 2,600pCi/min/m².

A rate of concentration increase measurement at the head of the raise over a lightly wetted muck pile gave an average rate of 3.48pCi/min/L. The muck pile reduced the raise dimensions to approximately 1.2x2.2m so this rate of rise is equivalent to an average surface release rate of 1,300pCi/min/m². Using the same figures for the release from the walls and back, this gives an estimate of 3,200pCi/min/m² for the release from the muck pile alone. Given the uncertainties this is not very different from the broken ore estimate.

The average radon release rate from raise surfaces in general is estimated at 1,000pCi/min/m², however the major source of radon in the raise is the muck that covers the foot wall, and comprises the muck pile. The radon release rate is 2,600 - 3,200pCi/min/m² - or about 4 to 5 times higher than the "typical" release rate from unbroken ore surfaces.

8.2 Radon Release from Blasting

The blast extensively fractures the rock, and instantly releases a fraction of the radon otherwise trapped in the rock pores. This release determines the radon concentrations in the raise after the blast. The central blasting system used today requires that the mine be cleared before the blast so it was not possible to measure the concentration in the raise immediately after a blast. A remote continuous radon monitor was not available for this study, so the concentration was estimated by a two step procedure.

The compressed air was left on in the raise, and the mine was re-entered as soon as possible after the central blast. The site was reached 26 minutes after the blast. Visibility at the slusher bench was poor, with smoke density at the mouth of the raise so high that a cap lamp beam could only penetrate it to a distance of 1m, and concentrations of 350ppm CO, 5ppm NO_2 were present there. As concentrations would be higher in the raise, it was not felt safe to enter, and so only radon concentrations in the air at the mouth of the raise were measured. The peak value was 300pCi/L. After the blasting fumes had been cleared from the raise by the compressed air, the air was turned off at the header, to allow radon concentrations to build up overnight. The next morning radon concentrations at the head of the raise were 1400pCi/L. The dilution of the raise air at the slusher bench was measured by turning on the compressed air at the same flow rate as the previous day. The peak value of radon concentration at the mouth of the raise was 226pCi/L. The radon concentration in the raise following the blast is therefore estimated at (1400x300/226)=1850pCi/L.

On the assumption that the entire raise was filled with radon to this concentration, based on the observation that blasting smoke rapidly filled the raise after firing a missed hole, the total amount of radon released in the blast was 400×10^6pCi. The rock contains about 1000pCi radon/cm³, and the round amounted to about 9.5m³ of broken rock, so this release is equivalent to about 4% of the radon in the ore. This is comparable to the 5% reported by Thompkins (Th 83).

8.3 Thoron Release Rate

When compressed air was used to ventilate the raise at low rates, the thoron daughter (ThB) concentration in the air leaving the raises was 0.8-1.6pCi/L when ventilation rates were in the range of 90 to 120L/s - based on 11 measurements. These concentrations are equivalent to ThB supply rates of 120-170pCi/s, or a nominal ThB release rate of 16-22pCi/min/m². This is a ThB atom production rate of 32,000 - 44,000atoms/min/m². In these

conditons, the thoron atom production rate will be the same (32,000 - 44,000atom/min/m²) equivalent to a thoron activity flux of 11,000 - 15,000pCi/min/m².

Simple diffusion theory predicts (Appendix 7) that for a material containing equal activities of radium and thorium, the flux of thoron atoms from the surface will be 1/80 of the radon atom flux. The local activity concentration of thorium - as shown by the spectrometer readings in Table 1 was about 30% of that of uranium, so the expected thoron atom flux is 1/270 of the radon flux. The average radon atom flux of 1000pCi/min/m² is equivalent to 18×10^6atom/min/m², so diffusion theory expects an average thoron flux of 65,000atom/min/m². This is more than 50% higher than the measured value.

A possible explanation for this shortfall is that the water released during drilling ran down the raises, and kept the muck on the floor wet. A thin film of water on the surface of a rock fragment would delay the atoms escaping from the rock, and greatly reduce the flux of thoron relative to radon (see Appendix 7). If the walls and back release thoron at their diffusion theory values, the wet muck is releasing thoron at about 20% of that value - i.e. 40,000atom/min/m², or 15,000pCi/min/m². A similar ratio of thoron to radon release is assumed for the muck pile or 18,000pCi/min/m².

8.4 Work Place Size

The cross section of the work place is set by the raise dimensions, but the effective length is set by the length of the mixing zone produced by the ventilation. This ranged from 5m, when the drill was the only source of air, to as long as 12m when additional air was supplied from an open valve on the air pipe. A typical mixing length for compresses air ventilation was about 10m. When auxiliary ventilation was in use, the mixing length was about 7-8m.

8.5 Ventilation Rate

The rate at which the raise head was ventilated by compressed air was measured at between 6 to 20 minutes per air change, depending on the amount of additional air supplied and the fraction of the time the drill was operating. A typical ventilation period during drilling was 10 minutes. When the auxiliary ventilation system was in operation, the period was about 1 minute.

8.6 Radon Daughter Deposition Velocities

The deposition velocity of free RaA was estimated in Section 5.3 as 0.1-1.0cm/s. A nominal deposition velocity of 0.5cm/s is chosen for conditions of moderate air movement. The deposition velocity decreases with air turbulence, so for natural ventilation conditions when turbulence is very small, a deposition velocity of 0.10cm/s was estimated, based on the observed ratios of radon and daughters in those conditions.

The effective deposition rate of attached daughters was low, for the ratio of RaB to RaC under low ventilation conditions was close to unity, suggesting a removal rate by deposition of less than $0.1h^{-1}$. For the surface to volume ratio of the raise, this gave a deposition velocity for attached daughters of $1.6x10^{-3}cm/s$ (0.001m/min). This is about 6 times higher than the gravitational setting velocity of the 0.2-0.3um particles to which the daughters are attached, but only 25% of the value measured in the surface environment.

Deposition velocity of attached daughters is not very sensitive to air movement, so this value is assumed to apply to all ventilation conditions. With such a low velocity, the deposition of attached daughters can be ignored, except at extremely low ventilation rates, e.g. natural ventilation.

8.7 Attachment Rate

The attachment rate of radon daughters to the atmospheric aerosol depends largely on the concentration of aerosol particles in the 0.2um range. Due to the failure of the CN counter, it was not possible to measure that concentration, and attachment rate was etimated indirectly from the ratio of radon to RaA, and the unattached fraction of RaA. The attachment rate was always high. Inferred values for mine air ranged from $3-10min^{-1}$, for drill exhaust air in excess of $20min^{-1}$, and compressed air alone $2-8min^{-1}$. The attachment rate did not seem to be affected by dust releases - probably because the estimates are not very accurate, and the dust particles released were generally larger than the preferred attachment size range of 0.2-0.3um.

8.8 Mine Air

Average values for present day mine air at the experimental site were 27pCi/L, 0.12WL(R), 0.13WL(T), $X=7m^{-1}$. In 1958-59, the average WL(R) in "airways and travelways" was 0.7WL(R). In the absence of other information, it is assumed that the ratios of radon and thoron were comparable to those observed today, and that typical mine air of that period was 140pCi/L, 0.7WL(R), 0.7WL(T). The attachment rate is assumed to be higher at $X=10min^{-1}$ as a result of higher particulate concentrations resulting from the "fire when ready" blasting system.

8.9 Summary Table

The parameters for computer modelling are summarized in Table 6.

9. COMPUTER MODELLING RESULTS

The steady state concentrations in the raise and at the slusher bench were calculated for compressed air and auxiliary ventilation at a number of different locations using the program MINES, and compared with the observed values. Agreement was good, as shown in Table 3 of Appendix 2, and gave confidence that the model and parameters were realistic.

The program TRAISE, described in Appendix 3, was used to calculate the time variation in concentrations at the raise head as conditions changed. The nominal raise mining cycle of 1957-58 as given in Appendix 1 was used as input, with the parameters derived above. The results are shown in Figure 6, and should be compared with Figure 4, which shows the values measured under similar conditions in the experimental program.

TRAISE reproduces all the features observed in the experimental study - the rapid decrease of concentrations following ventilation with compressed air, the increase to 1WL(R) during scaling and slushing, the steady decrease to 0.05WL(R) during drilling, and the changes in WL(R)/WL(T) ratio with ventilation. This gave confidence that both the model and parameters used were realistic.

9.1 Exposure Estimates

The exposure of the miners to radon and thoron daughters under conditions simulating those of the 1950's could be estimated from the observed concentrations, but the ability of TRAISE to calculate realistic concentration estimates under a variety of conditions enables us to calculate exposures in a standardized manner. Given standard work cycles, the exposure of the 1950's miner and that of today can be calculated and compared. The uncertainty in these calculations is mainly due to uncertainty in what length of time was spent in a task, and the ventilation conditions, rather than in the model and its parameters.

The exposure of a 1950's miner to radon and thoron daughters at the head of a raise was calculated by numerical integration using the times and ventilation conditions given for the typical 1950's raise mining cycle in Appendix 1. The miner is not in the raise during slushing, and so his exposure for that phase was estimated on the basis that the miner entered the raise twice for 5 minutes to check on progress, and that it took 10 minutes to set up the drill at the end of slushing. The concentrations in the raise during these entries were calculated by TRAISE, and the concentrations at the slusher bench were assumed to be the same as 1950's mine air - 0.7WL(Rn), 0.7WL(T). The calculated exposures for each phase of the cycle are shown in Table 7.

Most of the exposure is received during the early part of the shift when concentrations are high, due to minimum ventilation. It was mentioned by some miners that compressed air was not always left on after the blast, but turned on only when the miners arrived at the work site. The raise was then entered after a delay of about 15 minutes to clear the fumes from the

face. This was clearly a maximum case, and calculations were carried out by TRAISE so that the total exposure could be estimated. As the waiting miners would be exposed to high concentrations in the air forced out of the raise while they waited on the slusher bench, the concentrations there were assumed to be 20% of those in the air exiting from the raise (ca9WL), based on the values observed in the experimental program. Concentrations at the slusher bench during slushing were taken to be the same as mine air 0.7WL(R), 0.7WL(T). The exposure calculated for this case is also shown in Table 7.

For comparison purposes, the exposure of today's miner was calculated for the same mining cycle but with auxiliary ventilation providing mine air at 0.14WL(R) and 0.14WL(T) to the head of the raise and to the slusher bench. These exposures are also shown in Table 7.

Under the most favourable conditions (continuous ventilation with compressed air), the exposure of the 1950's miners to radon daughters was not much more than double the exposure of today's miners, but if the raise was left completely unventilated it could have been as much as 10 times higher. On the assumption that the air was left blowing 5 days out of 6, the average exposure of the 1950's miner is taken to be about 3.4WL.h(R), 1.2WL.h(T) per shift, equivalent to shift average concentrations of 0.48WL(Rn), 0.17WL(T). Although 60% of the time was spent drilling, that phase accounted for only 20% of the radon daughter exposure and 15% of the thoron daughter exposure.

Reported raise measurements for 1958-59 range from 0.1 to 4.2WL (Ha 76). This is comparable to the range of values measured in this experimental program over all phases of the mining cycle and over all locations in the raise. As the 1950's measurements were presumably made in raises at different stages of completion, and at various phases of the mining cycle, this agreement is about as good as can be expected. The average of 1958-59 raise measurements is 0.8WL, which is nearly double the estimated shift average exposure. In view of the low radon daughter concentrations measured in the raise during drilling, it would seem reasonably certain that this value represents a conservative estimate of the average concentration to which raise miners of that time was exposed.

10. CONCLUSIONS

Driving pilot raises with only compressed air for ventilation was believed to represent a maximum exposure case for miners before the introduction of forced auxiliary ventilation. Imitation of 1950's practices in a pilot raise found that compressed air provided effective local dilution near the point of release, and that concentrations could vary greatly depending on when and where they were measured. Concentrations at the face when compressed air was blowing to flush out blasting fumes, and when it was released by drilling were 0.05–0.1WL. When the compressed air was turned off for scaling or slushing, concentrations initially rose at 0.5WL/h, reaching maximum values of about 10WL overnight. Concentrations near the raise mouth were in the region of 0.8WL when compressed air was on, and when it was off would rise to maximum values of about 8WL overnight.

Radon release and daughter removal rates derived from independent measurements in the raise were used as input to the computer model, which reproduced the observed variations in concentration with time. Computer simulation of the time variation in concentrations showed that the 1950's raise miner received most of his exposure to radon and thoron daughters in the early part of the shift. Concentrations in the raise were high during scaling, slushing and roof-bolting, and considerable time was spent on the slusher bench in mine air. Although most time was spent drilling, this operation gave only a small exposure as concentrations during this phase were low.

Thoron daughter concentrations increase less rapidly than radon daughter concentrations when the ventilation is reduced. The ratio of thoron and radon WL's are equal when modern ventilation practices are used, but when the ventilation is reduced or cut off, the thoron WL is less than 0.3 radon WL. The exposure of raise miners to thoron daughters in the late 1950's was virtually the same as that of miners today.

Under the most favourable conditions – compressed air left on following the blast – the actual exposure of the 1950's raise miner to radon daughters was not much more than double that of present day miners, even though raise concentrations measured in the 1950's were about 5 times higher than at present. The reasons for this difference in measured WL and exposure are mainly that the guiding philosophy behind radiation measurements in the 1950's was "workplace control", not personal dosimetry, and so there was no reason to make measurements close to the miner.

If "upper limit" measurements are used to estimate the average concentration to which the miner was exposed, his exposure will be over-estimated. This systematic bias is more significant in the case of raise miners than for stope miners. The local dilution produced by the release of compressed air is much greater in the confined quarters of a raise than in the much larger stopes, where the general air circulation would be expected to carry the drill air away from the miner resulting in relatively constant concentrations in his vicinity.

Reported stope and drift concentrations in the late 1950's averaged 1.0WL (Ha 72), suggesting that on average, stope and drift miners at that time were receiving 7WL.h per shift, which is double our exposure estimate for the typical raise miner. It is quite probable, therefore, that the group receiving the highest radon daughter exposures at that time was not the raise miners, suggested by the Morrison Committee, but the stope miners. A specific study on the variations in the WL in the vicinity of stope miners throughout their working cycle, compared with general area WL measurements would be required to confirm this.

Although the introduction of auxiliary ventilation into raises may have only decreased the daughter exposure of raise miners by a factor of 3 compared with the late 1950's, the effect on exposure to quartz and uranium ore dust is much greater. The auxiliary ventilation air flow dilutes and removes the dust released by collaring and drilling many times more rapidly than air released from the drill, and reduces dust concentrations during slushing, both in the raise and at the slusher bench. As a result, the exposure of today's raise miners to quartz and uranium ore dusts is only a fraction of that to miners in the 1950's.

TABLE 1

EXPOSURE RATES

LOCATION	SCINTILLOMETER						
	SRD mR/h	PRM-7 mR/h	Thorium Ct/s	Uranium Ct/s	>1.2 MeV Ct/s	>400 keV Ct/s	>80 keV Ct/s
Raise:							
E0	-	2.1	125	300	1,190	8,600	36,500
E25	1.8	2.3	120	410	1,400	10,300	42,000
E50	1.3	1.8	90	250	910	7,200	32,000
E75	1.5	2.2	100	290	1,050	8,200	36,000
E100	-	2.6	115	370	1,300	10,000	43,000
E125	-	2.8	102	540	1,500	11,000	45,500
E150	-	3.0	140	480	1,650	12,600	50,000
E175	-	2.6	110	490	1,500	11,600	46,500
Slusher Bench:							
	0.7	0.9	-	-	-	-	-
	-	0.8	61	134	550	3,900	18,000
Cut-out Floor:							
	-	0.7	25	95	300	2,450	12,500
Airway:							
Ore Pass	-	1.2	45	230	520	4,050	20,500
Scour Area	-	0.2	12	40	125	910	5,150

SRD: R.A. Stephens Quartz Fibre Electrometer Dosimeter, 0-200 mR.

Scintillometer: EDA GRS-400 Integral Scintillometer.

TABLE 2

MINER EXPOSURE TO DUST-GRAVIMETRIC ESTIMATES

Date	Task	Time Start - Stop	Respirable Dust (mg/m^3)	Respirable Quartz (mg/m^3)
Feb. 22	Scale	8:28 - 9:15	6.26	ND
	Drill	9:15 - 12:30	2.84	ND
	Full Shift	8:29 - 13:55	0.82	ND
23	Scale	8:30 - 8:45	7.84	ND
	Slush *	8:45 - 10:10	2.08	0.15
	Rockbolt	10:10 - 10:50)	3.60	ND
	Drill	10:50 - 13:50)		
	Full Shift	8:30 - 14:00	0.84	ND
24	Scale	8:15 - 8:30	5.10	ND
	Slush *	8:30 - 9:45	2.98	0.15
	Drill	9:45 - 13:45	4.12	0.10
	Full Shift	8:15 - 13:45	0.89	0.04
27	Scale	8:30 - 9:00	2.15(1)	ND
	Slush *	9:00 - 9:50	3.18	ND
	Wait	9:50 - 11:15	2.15(1)	
	Drill	11:15 - 13:45	6.59	ND
	Full Shift	8:30 - 13:45	1.06	0.19
28	Scale and Pipe	8:40 - 10:10	18.8(2)	0.72(2)
	Drill	10:10 - 13:40	Sample Lost	
	Full Shift	8:40 - 13:40	2.04	0.31
29	Scale	8:40 - 9:00	1.81(1)	0.08(1)
	Slush *(3)	9:00 - 11:30	4.39	0.82
	Scale	11:30 - 13:45	1.8(1)	0.08(1)
	Full Shift	8:40 - 13:40	2.57	0.02
Mar. 1	Drill	8:30 - 13:15	6.40	1.4
	Clean-up	13:15 - 13:45	4.12	ND
	Full Shift	8:30 - 13:45	8.96	ND

Notes:

* Most of time spent on slusher bench, but raise entered at intervals to check progress.

(1) Same filter used for all these tasks.

(2) Piping blown out released very large amount of iron oxide dust.

(3) Large piece of muck blasted - more time spent in raise than usual, plus higher dust concentrations.

ND - Less than 0.1 µg quartz total on filter.

TABLE 3

UNATTACHED FRACTION

Date	Time	Location	Comment	Unattached RaA % (SD %)
2:22:84	8:52	SB	mine air	0
2:23:84	10:31	SB	mine air	1.5 (2.5)
2:27:84	7:50	US	mine air	too low
2:27:84	8:33	E170	compressed air vent	9 (1)
2:27:84	11:37	W145	drilling air	too low
2:28:84	8:59	SB	mine air	0.6 (1.5)
2:29:84	7:57	E170	compressed air vent	4.3 (1.5)
2:29:84	8:43	E50	compressed air vent	2.0 (0.5)
3:01:84	9:49	DS	mine air	9 (5)
3:04:84	12:30	SB	mine air	9 (1.5)
3:02:84	8:22	W50	no ventilation	4 (0.5)

TABLE 4

DEPOSITION MEASUREMENTS

Date	Time	Location	Total Surface Activity pCi/m^2	Equivalent RaA Deposition Velocity Total (V_T) cm/s
2:21:84	11:48	SB	6,000	38×10^{-2}
2:21:84	12:22	W50	6,800	4.5×10^{-2}
2:22:84	9:50	SB	8,200	6.0×10^{-2}
2:23:84	11:54	SB	10,800	8.1×10^{-2}
2:28:84	11:55	SB	19,000	10×10^{-2}
2:28:84	13:19	E50	3,800	1.4×10^{-2}
2:29:84	8:50	E50	9,500	2.4×10^{-2}
3:01:84	7:38	SB	7,500	4×10^{-2}
3:01:84	10:14	SB	18,000	12×10^{-2}
3:01:84	11:05	W25	8,200	1.9×10^{-3}
3:01:84	12:23	SB	9,000	5.7×10^{-3}

TABLE 5

RELATIVE HUMIDITY

Date	Time	Location	Wet Bulb (^{o}C)	Dry Bulb (^{o}C)	R/h (%)
2:20:84	11:00	SB	9	11	78
2:20:84	12:52	SB	7.5	9.5	78
2:21:84	13:40	SB	8.5	10	82
2:22:84	11:20	SB	8.5	10.5	77
2:23:84	10:22	SB	8.5	11.0	83
2:23:84	13:30	SB	9	10.5	82
2:24:84	8:53	SB	9.5	11.0	82
2:24:84	12:17	W120	9.0	9.0	100
2:24:84	12:28	SB	10	11.5	83
2:27:84	11:20	SB	8.5	11.0	72
2:28:84	12:05	SB	7.5	10.0	72
2:28:84	12:17	E180	7.5	8.0	94
2:29:84	10:00	SB	8.5	10.5	77
2:29:84	13:08	SB	8.5	10.5	77
3:01:84	10:25	E180	8.0	8.0	100
3:01:84	13:05	SB	8.0	10.0	74
3:02:84	8:50	SB	8.5	10.0	82

TABLE 6

SUMMARY OF PARAMETERS FOR COMPUTER MODELLING 746 RAISE

Air Quality

General mine air (today):

Rn=27, RaAf=0.8, RaAa = 20, RaBf = 0.01, RaBa = 12.0, RaCa = 10.0 pCi/L

Th = 10, ThB = 1.0, ThC = 0.5 pCi/L

Attachment rate (X) = 7 m^{-1}

Mine air (1950's):

Rn = 140 pCi/L, 0.7 WL(Rn), 0.7 WL(Tn), X = 10

Drill air:

Rn, Tn = 0, X = 20 m^{-1}

Compressed air:

Rn, Tn = 0, X = 5 m^{-1}

Release Rates

	Rn	Tn
Ore walls (pCi/m^2/min)	660	16,000
Wet muck floor	2,250	6,000
Wet muck pile	2,700	9,000
Back	60	2,000
Average for entire raise	900	10,000

Deposition Velocities

Free daughters - low ventilation	0.06 m/min
- normal ventilation	0.30 m/min
Attached daughters - all conditions	0.001 m/min

TABLE 7

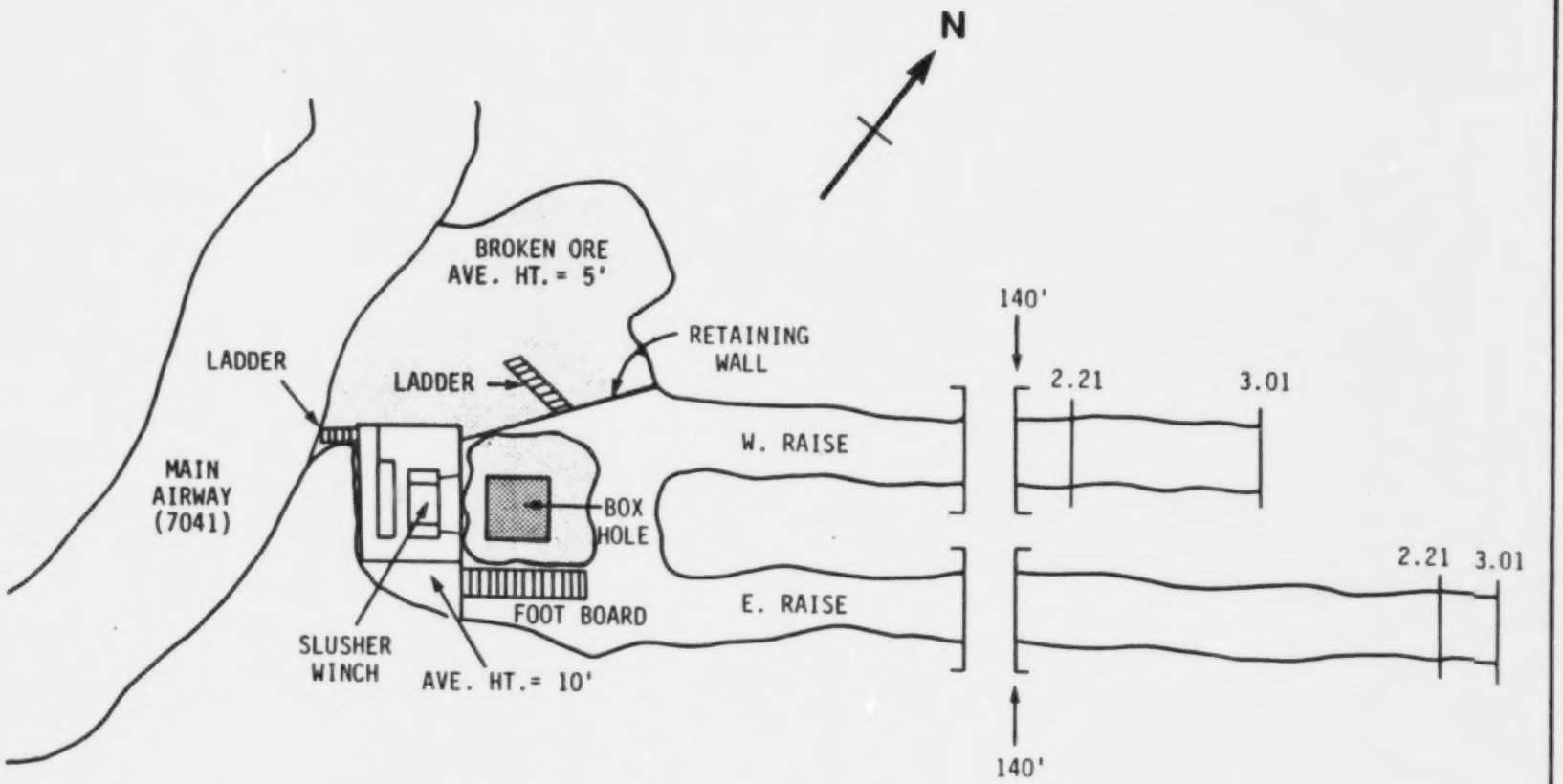
CALCULATED MINER EXPOSURES

Exposure	Typical Case		High Case		Auxiliary Ventilation	
	WL.h(R)	WL.h(T)	WL.h(R)	WL.h(T)	WL.h(R)	WL.h(T)
Wait to clear	-	-	0.62	0.02	-	-
Wash/scale	0.40	0.14	5.01	0.21	0.14	0.13
Slush						
- Entries	0.14	0.05	0.8	0.06	0.02	0.02
- Slusher Bench	0.58	0.58	0.58	0.58	0.12	0.11
Roof Bolt						
- Set-up	0.16	0.05	0.73	0.07	0.02	0.02
- Drill	0.32	0.11	1.43	0.14	0.06	0.06
Drill	0.38	0.20	0.77	0.2	0.48	0.44
Load	0.08	0.04	0.08	0.04	0.07	0.07
Total WL.h/shift	2.06	1.17	10.0	1.32	0.91	0.85
Average WL	0.29	0.16	1.38	0.18	0.13	0.12

TABLE 8

TABLE OF KONIMETER READINGS

Time	22 Feb.	Task	23 Feb.	Task	24 Feb.	Task	27 Feb.	Task	28 Feb.	Task	29 Feb.	Task	1 Mar.	Task
8:45					150	—							<50	—
9:00			<50	—	300	SLUSH	75	—					200	
9:15	<50	—	275		450		200				100	—	500	
9:30	<50	SCALE	<50	SLUSH	440		700	SLUSH			380		380	
9:45	100		240		300		300				670		1000+	
10:00	450		210		400	BOLT	680				450		1000+	
10:15	100		110		1000+		600				700	SLUSH	950	DRILL
10:30	100		60		1000+		250				1000+		300	
10:45	<50		700		400		400	WAIT	1000+	—	1000+		200	
11:00	75		550		450		450		1000+		270		180	
11:15	<50		250	BOLT	150		1000+		200		<50		120	
11:30	<50		70		<50		900		250		1000+	SCALE	80	
11:45	<50	DRILL	70		60		300		100		550		80	
12:00	<50		<50		<50		100		100				230	—
12:15	<50		75		80	DRILL	<50	DRILL	70	DRILL			80	
12:30	<50		110		<50		<50		60				70	
12:45	<50		90	DRILL	<50		80		50				160	CLEAN UP LOAD
13:00	60		320		<50		70		100				60	
13:15	50	—	1000+		<50		<50		70				120	
13:30			180		1000+		<50	—	100	—			80	
13:45			420	—	400	—							<50	—
14:00														
COMMENT	WEST RAISE AUX. VENT ON		WEST RAISE REDUCED VENT.		WEST RAISE DRILL AIR ONLY		WEST RAISE DRILL AIR + EXTRA		EAST RAISE DRILL AIR + EXTRA		EAST RAISE DRILL AIR + EXTRA		EAST RAISE DRILL AIR + EXTRA	



Average Slope of Raises = 17^{o}

Scale = 1:240

FIGURE 1 746 RAISE PLAN

DSMA ATCON LTD.

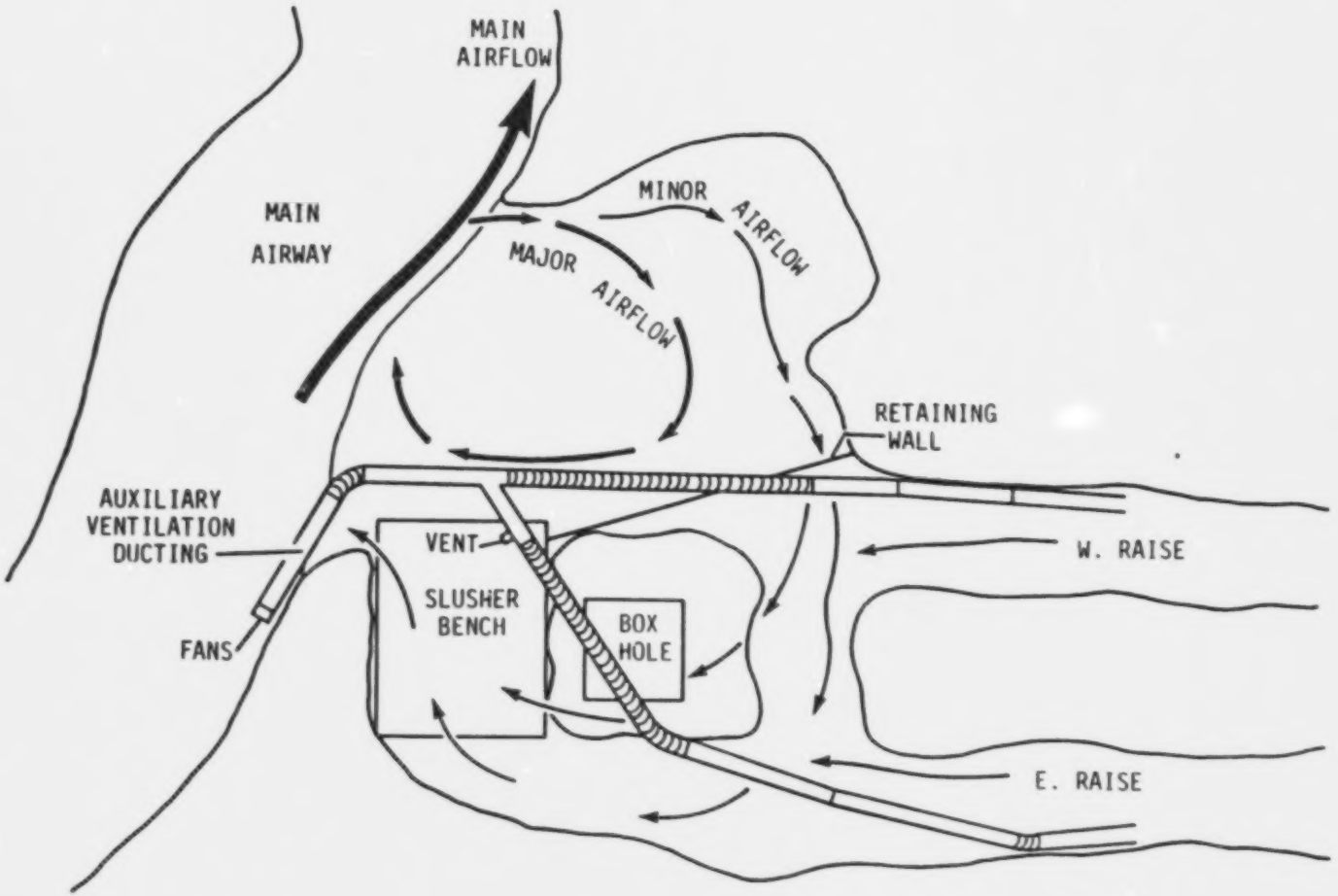
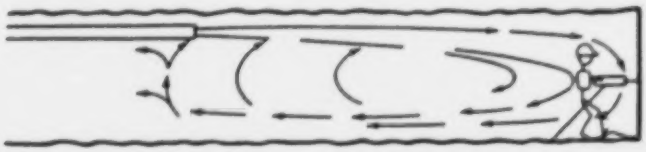
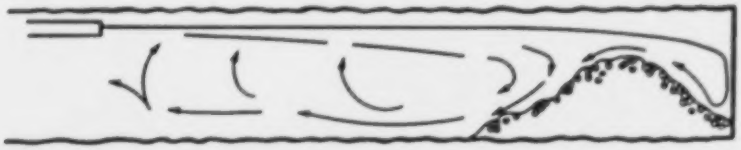


FIGURE 2 736 RAISE - VENTILATION

DSMA ATCON LTD.



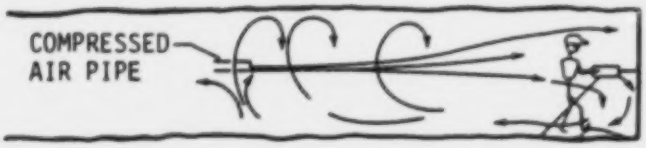
A. AUXILIARY VENTILATION



B. AUXILIARY VENTILATION OVER MUCK PILE

C. AUXILIARY VENTILATION TOO FAR BACK

D. DRILLER WITHOUT ADDITIONAL AIR



E. DRILLER WITH ADDITIONAL AIR

F. NATURAL VENTILATION

FIGURE 3 VENTILATION PATTERNS IN A RAISE

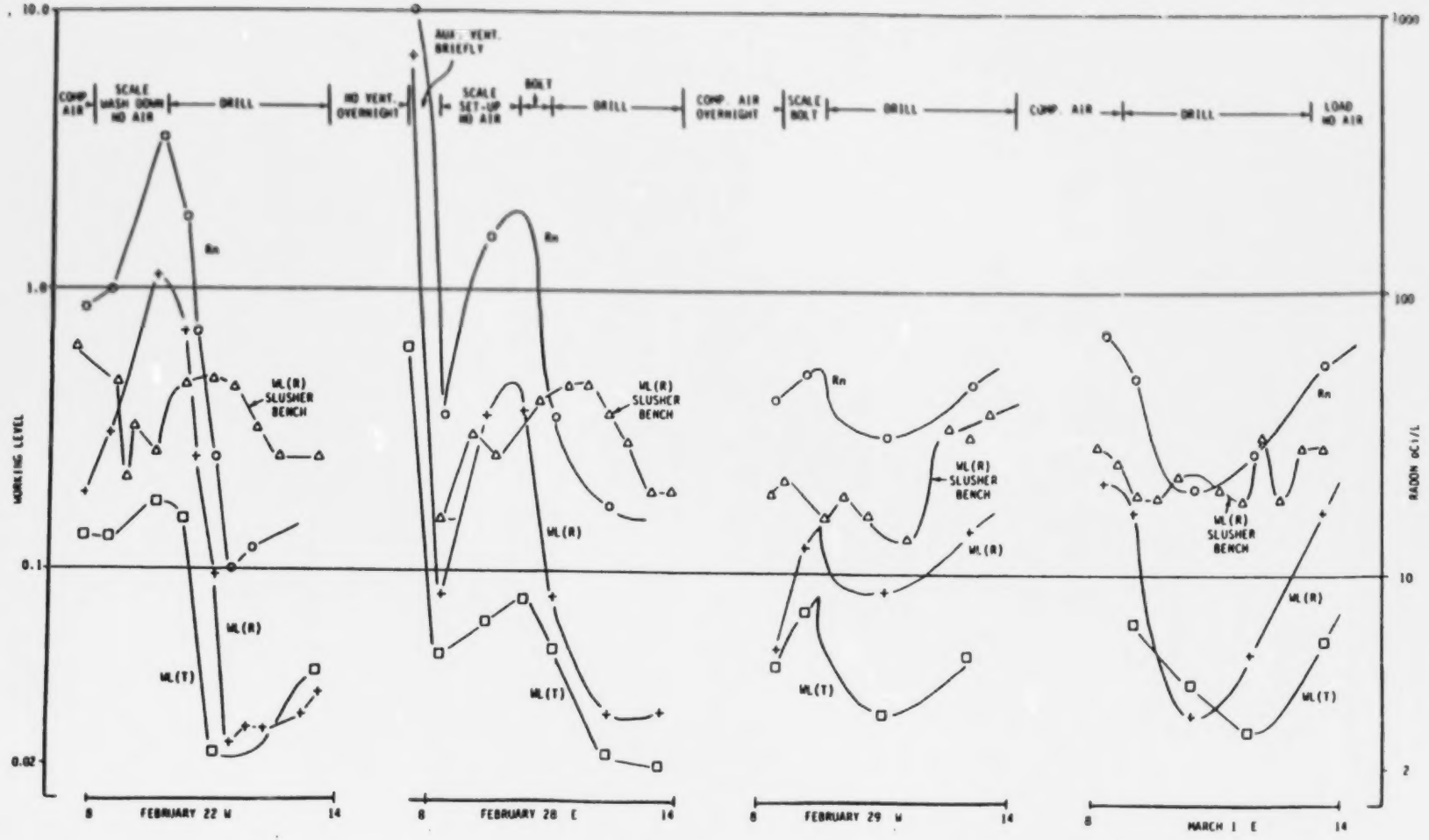


FIGURE 4 OBSERVED VARIATION IN RAISE RADON AND WORKING LEVEL

DSMA ATCON LTD.

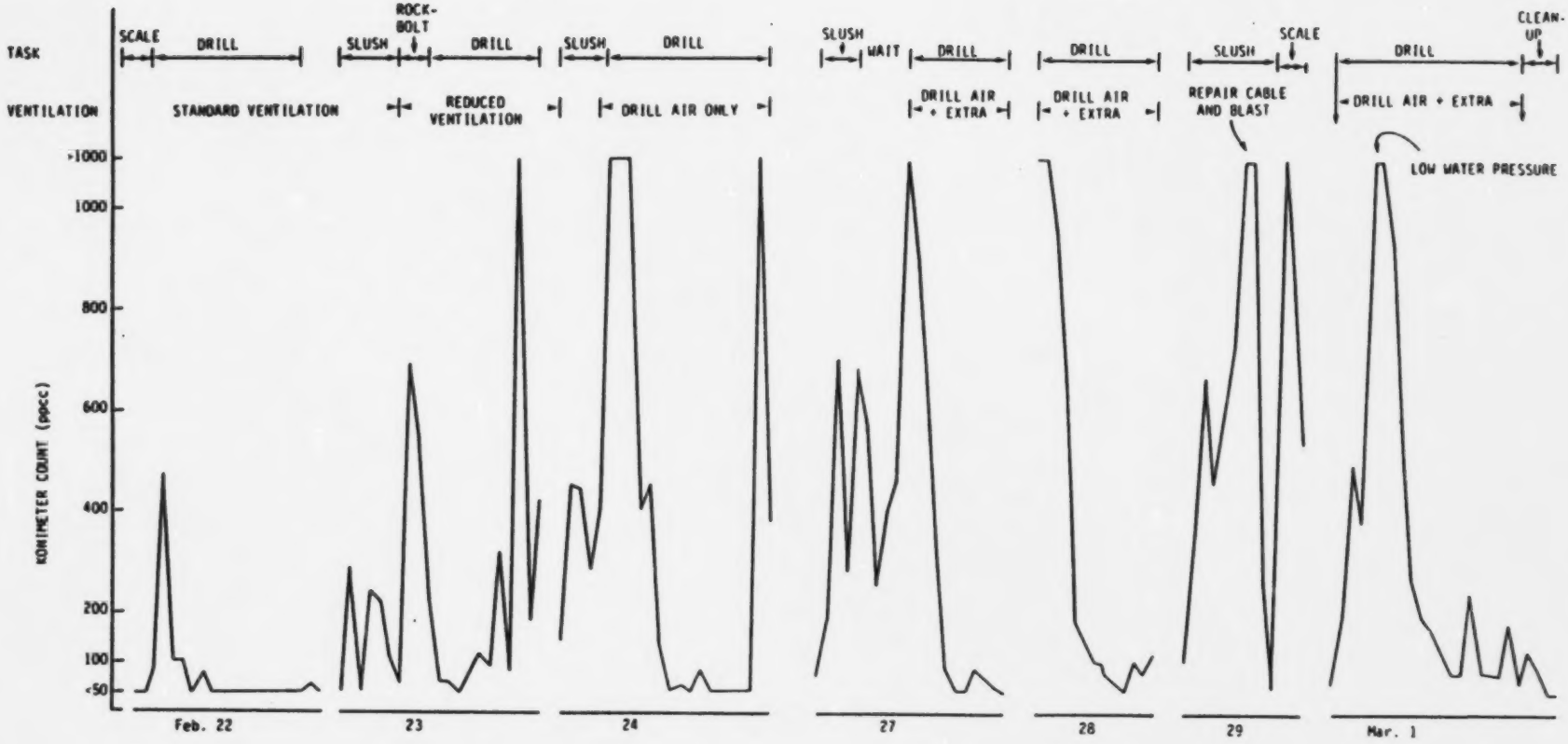


FIGURE 5 MINER EXPOSURE TO DUST - KONIMETER ESTIMATES

DSMA ATCON LTD.

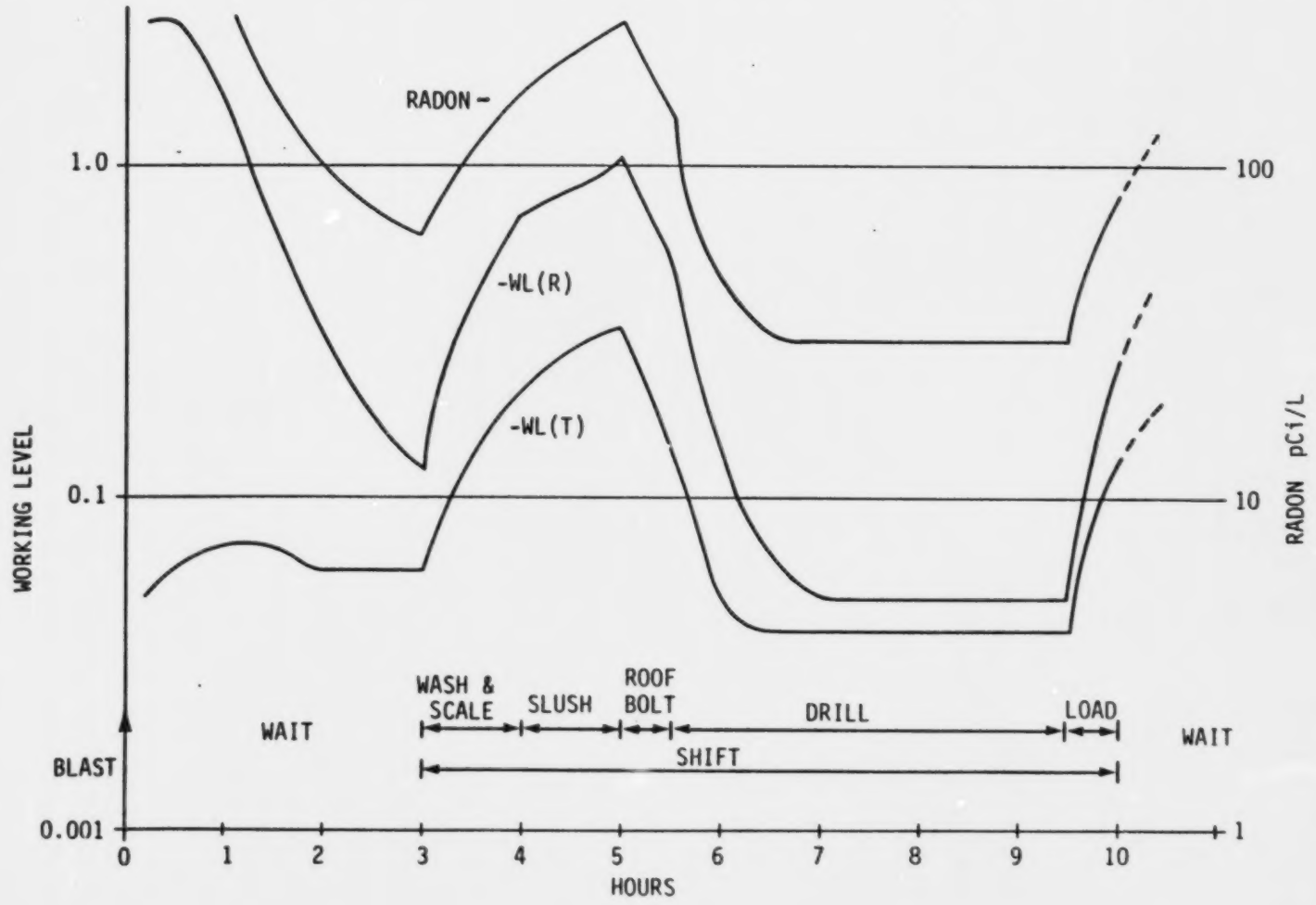


FIGURE 6 CALCULATED VARIATION IN RAISE RADON AND WORKING LEVEL

DSMA ATCON LTD.

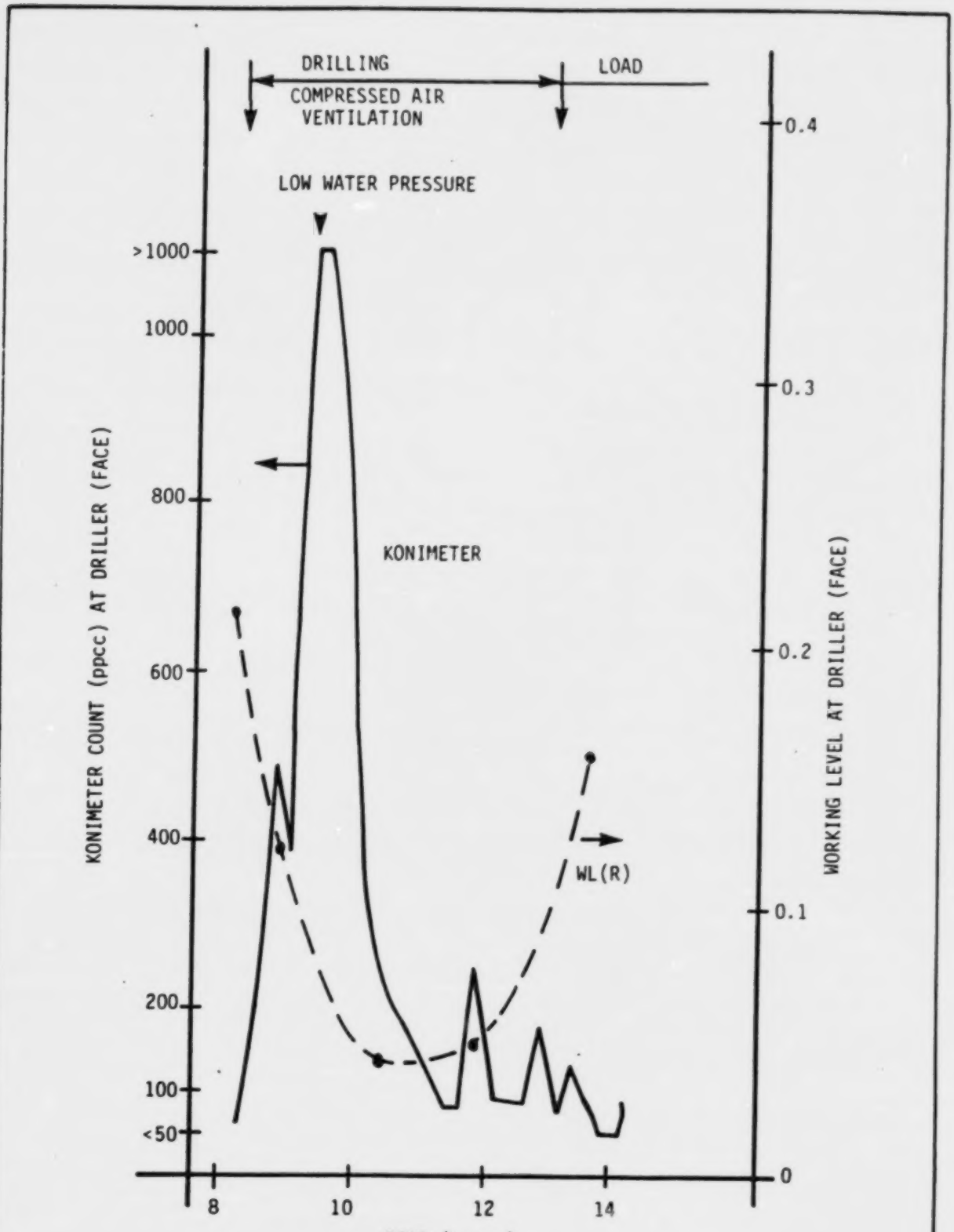


FIG. 7 INDEPENDENT VARIATION OF DUST AND WL

DSMA ATCON LTD.

APPENDIX 1

MINER INTERVIEWS

ANALYSIS OF ELLIOT LAKE WORK PROFILE STUDY INTERVIEWS

1. INTRODUCTION

As part of a program to determine what mining practices were at Elliot Lake in the late 1950's, miners who were employed in the mines at that time were interviewed. Miners were selected jointly by representatives of mining companies and the Union from the seniority lists of the two mining companies, and from the Union list of retirees, and those living in Elliot Lake were invited to participate. Attempts were made to have approximately equal representation from each mining company. The interviews were carried out after work hours by 4 members of the AECB Elliot Lake staff, who had mining experience. One of them had been a mine worker in Elliot Lake in the late 1950's. Their experience was valuable in understanding the miners statements. A simple statistical analysis of the data is shown in Table 1.

2. MINING CONDITIONS

The miners were asked to recall conditions of 25 years ago, at a time when conditions were changing rapidly. It is not surprising that their recollections differ in detail, but a general picture of the mining conditions of the time can be generated. Some topics are dealt with separately below.

2.1 Dust Control

Although the use of water sprays to reduce dust release from blasted ore was a well established technique at the time, they were not generally used. Only 7 of 31 miners remembered their use to wet ore after the blast. Muck was wetted down with a hose at the same time as the face and back were washed down - generally the first task on a shift. This was insufficient to fully wet the muck, and it was generally dry when slushing or mucking started. Water was used more extensively during slushing, with 21 of 36 miners remembering the use of hoses or sprays to

wet the ore in the mining area, or at the ore chute. Several miners stated that the use of water and sprays increased greatly after about 1960, so the differences in water use may be a function of differences in recollection. In any case, the most common adjective describing the air during slushing was 'dusty'.

There was enough room in stopes for slushing and drilling to take place at the same time, a practice reported by 22 out of 30 miners. The other 8 miners worked in drifts and raises where there was insufficient room at the face for a driller to operate safely close to the slusher block and cables, and drilling and slushing took place separately.

Dust generation while drilling was reduced by the use of water flushed drills. Only 9 miners out of 38 recollected themselves or others collaring dry, and no one drilled without water. The drills often had valves on them so that water could be shut off. Of 35 miners, only 15 said that there were no water valves, or that valves had been removed, and of the remaining 20 miners, 8 mentioned that stoper drills had valves, but that jackleg drills did not. (Stoper drills were used to tighten roof bolts - an innovation at the time - and water was not needed for that task.) Drilling dry was known to release large amounts of dust, so perhaps dry collaring was not as common as the number of water valves might indicate.

2.2 Mining Cycle

The mining cycle varied according to whether a man worked in a large stope or small pilot raise, but in general when the team entered an area after a blast, one man would wash down the face, wet the muck pile, and scale while the other would set up equipment. A hole would then be drilled to attach the slusher block to the face, and the face would be slushed clear. One man would then scale and rockbolt while the other slushed, and then both men would drill at the face,load, and blast. (This procedure was described by 21 miners.) In large stopes there were often separate drilling and slushing teams, who would work on opposite sides of the stope, or with the slusher operating below the drillers. In this case, drilling and slushing were continuous for almost the entire shift (times of 5-8 hours reported by 15 miners).

In raises and pilots there was not enough room to drill beside the slusher block and cables, and so slushing took place separately (mentioned by 8 miners). The cycle then was to wash down, scale and set up (less than an hour) slush for 1-2 hours (8 miners) to clear out the raise, scale and rock bolt (1-2 hours), then both would drill at the face for about 4 hours including loading (10 miners). In other cases, one shift drilled, loaded and blasted, and the other shift slushed out, scaled, and bolted (3 miners).

A mucking machine was used in some drifts to lift the broken ore into waiting cars, but in other drifts the ore was slushed up a ramp into the cars. There was usually enough room there for a man to drill at the face while mucking or slushing took place. The use of a jumbo drill in drifts was reported by 2 miners.

The standard length of shift was 8 hours, with 2 shift working recalled by 25 miners, and 3 shift by 10 miners. Work weeks of 6 or 7 days were recalled by 6, and extensive overtime by 10. A 'fire when ready' blasting system was in use at least part of this period (reported by 11 men) so shifts could be extended until the crew completed their tasks.

2.3 Ventilation

The air supplied to the working area was not always clean, as shown by the comments from 12 men that the air was smokey, or that fumes were present from blasts fired in other locations during their shift. One man had been gassed by powder fumes from a blast in an adjacent stope. The stopes were connected between the main air circuits and had through ventilation driven by the pressure difference between supply and exhaust airways. Only 1 miner mentioned the use of fans in a stope.

Blind end tunnels require forced ventilation to remove blasting fumes from the work area, and this was initially provided by leaving the compressed air line 'cracked open' after the holes were loaded. The air released diluted the fumes and moved them away from the face, so even if an early entry was made, conditions in the working area were better than those in the tunnel. It was usual to turn off the compressed

air while the face and back were washed down and equipment set up, so until drilling started for rockbolting, there was no ventilation from this source.

At first pilot raises were ventilated only by compressed air, and fans were used in the larger drifts. A variety of duct and fan sizes were used, with 12" and 20" duct being the most common. The end of the duct was usually 50 to 75 feet from the face - far enough to avoid blast damage as the rigid ducting was not moved back for the blast. The miners were generally responsible for extending the last length of ducting as the face advanced, but a pipe crew maintained the rest of the ducting. Fan ventilation was introduced into pilots in 1960 or thereabouts (date recalled by 2 men), and 12" duct was the usual duct size there at that time. The use of a fan without ducting blowing up a pilot was recalled by 1 man.

3. COMMENTS

The picture of conditions given by these interviews was compared with that presented by contemporary internal reports from Quirke mine (Ri 58) and presentations to the Morrison Commission (Mo 59), which carried out an investigation in 1959 mainly into conventional mine safety in Elliot Lake. It is a valuable source of general information about mining practices of the time.

In 1959 there were 4950 underground workers. Denison employed 905, Nordic 373, and Quirke 477. Our survey group over-represents the Nordic/Quirke group relative to Denison, and badly under-represents the other mines that employed 70% of the miners. To some extent this is a reflection of the very high turnover in the industry at that time - over 15% a year, and the subsequent mine closures when the contracts were not renewed.

3.1 Dust Control

The Quirke (Ri 58) report shows that dust concentrations were almost halved between late 1957 and early 1958. In this period the use of water hoses had been encouraged, water blasts in development ends had been made mandatory, and a layout had been drawn up for establishing water blasts

in stopes. Improvements in ventilation control had increased the percent of stopes with air velocities higher than 40 ft/min from 13% to 61%. The results of these suppression and dilution measures on konimeter counts were:

	1958	1957
Drifts	314	762
Raises	849	1272
Stopes	305	758
Airways	344	388
Miscellaneous	635	1111

A presentation to the Morrison Committee by Dr. Gillanders on 'Industrial Hygiene Aspects of Uranium Mining' generally confirms the dust control situation. He claimed that the following measures were being taken in 1958, i.e. were not yet general practice at that time - removal of water valves from drills, water sprays following blasting, and frequent wetting of ore during scraping and loading. A presentation by the Stanleigh mine mentioned that they had made up 40 air/water blast nozzles, and had one in every working heading, and that they wetted both the muck and the muck pile.

All this indicates rather more attention to dust control than recollected by the miners. However, almost all of them started before these programs could have become routine, so their recollections probably reflect the overall situation prior to 1959.

3.2 Ventilation

Although large volumes of air were supplied to the mines, utilization could be poor. The Quirke report (Ri 58) identified 'wastage' (incorrectly routed airflows) of 120,000 cfm at a time when the total downcast was 300,000 cfm. Recirculation of air from stope to stope took place, as shown by the Union presentation to the Morrison Committee concerning blasting fumes in air supply drifts. The direct problems caused by a "fire when ready" system

had been largely overcome by 1959 by most mines adopting 2 shifts separated by 3 hours with a primary blast at the end of each shift. This gave 3 hours for the blasting fumes to clear. Some blasting still took place during the shift, in 'high priority headings with local exhaust ventilation' at Stanleigh, and for 'missed holes' at Quirke (Mo 59).

The use of auxiliary ventilation was mentioned as a well established practice in Dr. Gillanders' presentation which stated that in 1958 there were 230 electric fans undergound in 7 mines, mostly 19" diameter (3,500 - 7,000 cfm), operated in conjunction with 'miles of metal ducting'. One of the goals was to have 40 ft/min air velocity at the face, but this was'difficult to implement'. This velocity requirement was for dust control, not radon daughter control.

The Quirke report (Ri 58) states that auxiliary ventilation (10" duct/ 19" fan)"had been found effective for dust control in a raise, and was needed in other raises", but there were problems with auxiliary ventilation, for the report also states that "duct leakage and long ducts were giving low air velocities in drifts despite fans placed in series" and "too many fans were poorly located and merely recirculated exhaust air". At that time there were 37 19" fans underground, 10,000 ft of 16" duct for drifts, and 830 ft of 10" duct. Additional 10" ducting was to be ordered for slot raises.

The need for auxiliary ventilation in long raises is mentioned in the Committee report, and confirms the general picture of auxiliary ventilation being used only in larger drifts. That report gives the following numbers of auxiliary fans in 1959 as Denison - 89, Nordic - 76, and Quirke - 74. This is an increase of 33 fans over the number at Quirke in 1958, so there had been a major expansion of the auxiliary ventilation system. This confirms the miner's recollections that auxiliary ventilation became common around 1960.

4. RADIATION MEASUREMENTS

Relatively few radon daughter measurements were made in the mines initially - the Code of Practice then in use required only quarterly measurements at the same time as dust and ventilation surveys. The intent was basically for mine ventilation control, not to estimate the exposure of the miner to radon daughters or dust. Up to 1957 measurements were made by the original Tsivoglon method (three rate-meter counts), and the results were expressed in micro micro curies/litre of radon daughters. The 'tolerance' values then was interpreted as the alpha activity of radon daughters in equilibrium with 100 pCi/L radon and was generally estimated as one half the sum of the RaA and RaC' activities (Si 54). In 1958 the Kusnetz method (1 rate-meter count) was introduced, with a change from an activity standard to a potential alpha energy standard - the WL.

Although the behaviour of radon daughters was not well understood in the 1950's, it was known that the daughters attached themselves to aerosol particles. In the surface environment, these particles were atmospheric dusts 0.1 micrometer diameter. In mines, the mineral fragments of plus one micrometer diameter released during breaking and handling ores and rock had long been identified as a health hazard, and were generally referred to as 'dust'. As a result, there seems to have been a mental association between 'dust' levels and radon daughter levels with the expectation that if dust was high, then WL's would be high too, e.g. (Mo 60 ibid).

5. NOMINAL WORKING CONDITIONS

The information on the radiation and dust concentrations given in the Quirke Report (Ri 58), the Ham Report (Ha 76), and in a paper by R. Yourt (Yo 66) was combined with the time and task descriptions given by the miners to provide nominal working condition estimates for the reference period of the late 1950's. These were used as a basis for the computer modelling of concentration variations.

NOMINAL WORKING CONDITIONS

As an indication of general air quality in 1957 - 1959, dust and radiation measurements in 'airways and travelways' were:

		Maximum	Mean	Minimum
Dust ppcc	1957	--	388	--
	1959	--	344	--
WL	1959	8.1	0.77	--
	1960	2.27	0.58	--

PILOT RAISES (1957 - 1958)

Cross-section: 2.5 m x 2.5 m
Length: up to 80 m

Work Cycle (2 shift) 1957 - 1958

Activity	Duration (h)	Ventilation	Comments
Blast and wait to clear fumes	3.0	comp. air 50 cfm	No one present
Wash down, scale, set up	1.0	nil	Muck wetted down
Slush out	1.0	nil	No one in raise - high dust at slusher bench
Roof bolt	0.5	drill air 50 cfm arc	High dust from collaring
Drill	4.0	drill air 100-200 cfm	High dust from collaring. Moderate dust from drilling + dust from residual dry muck
Load	0.5	nil	

During 1958-1959 there was increased use of auxiliary ventilation and of watersprays.

Observations:		Maximum	Mean	Minimum
Dust ppcc	1957	--	1271	--
	1958	--	849	--
WL	1958	2.8	1.04	0.15
	1959	4.2	0.55 - 0.83	0.1
	1960	4.8	0.82 - 0.90	0.1

DRIFT

Cross-section: up to 3 x 6.5 m
Length: up to 250 m

Work Cycle (2 shift)

Activity	Duration(h)	Ventilation	Comments
Blast and wait to clear fumes	3.0	Aux.(5000 cfm)	No one present
Wash down, scale, set up	1.0	Aux.	Ore wetted down
Slush or muck out at face	1.0	Aux. + air from mucker	Dust from muck removal
Slush or muck out drift	5.0	Aux. + air from mucker + drill air	Dust from muck removal + drill dust
Roof bolt	1.0	Aux. + air from mucker + drill air	Dust from muck removal + drill dust
Drill 1-2 men	4.0	Aux. + air from mucker + drill air	Dust from muck removal + drill dust
Load	0.5	Aux.	

During 1958-1959 there was increased use of watersprays.

Observations:		Maximum	Mean	Minimum
Dust ppcc	1957		762	
	1958		314	
WL	1957	2.75	0.61	0.09
	1958	4.9	1.26	0.08
	1959	7.95	0.68 - 1.49	0.09
	1960	3.39	0.43 - 1.09	0.11

STOPE

Cross-section: up to 4 x 18 m
Length: up to 80 m

Work Cycle (2 shift)

Activity	Duration(h)	Ventilation	Comments
Blast and wait to clear fumes	3.0	Through (5-8000 cfm)	
Wash down, scale, set up	1.0	"	Muck wetted down
Slushing Crew			
Slush out	6.0	"	High dust from poorly wetted muck. Signaler in stope at slusher block
Drilling Crew			
Scale, roof bolt	1.0	" + drill air	High dust from slushing operation + drill dust
Drill	5.0	" + drill air	High dust from slushing operation + drill dust
Load	0.5	Through	Dust from residual dry muck

During 1958-1959 there was improved air direction and velocity control, plus more watersprays.

Observations:		Maximum	Mean	Minimum
Dust ppcc	1957		758	
	1958		305	
WL	1957	3.6	0.88	0.14
	1958	4.03	0.68 - 1.68	0.19
	1959	9.55	1.14 - 1.66	0.10
	1960	4.86	0.83 - 1.3	0.10

TABLE 1

Number Interviewed	42	
Prior Mining Experience	14	
Year of First Employment		
1955	2	
1956	9	
1957	16	
1958	11	
1959	4	
Mine of First Employment		
Nordic	15	
Quirke	9	
Denison	12	
Others	6	
Miners	35	
Supervisors	3	
Service Staff	4	
Mining Location		
Stope	20	Some miners worked in more than one location.
Raise/Pilot	20	
Drift	11	
Ventilation		
Compressed air only	5	
10" duct	3	
12" duct	7	
16" duct	2	
20"+ duct	10	
Distance from Face		
<30	3	
50	7	
75	6	
100	4	
150+	2	

APPENDIX 2

COMPUTER PROGRAMS

'MINES' -

A GENERAL PROGRAM FOR CALCULATION OF RADON THORON AND DAUGHTER CONCENTRATIONS IN AN UNDERGROUND TUNNEL NETWORK

Prepared by A.G. Scott

January 1984

The program assumes that all regions in a mine can be modelled as a combination of these two cases, and calculates the steady state concentrations resulting from the airflows and radon plus thoron releases in the tunnel network.

PLUG FLOW

In an isolated body of air, such as a plug of air moving down a tunnel without significant longitudinal mixing, airborne radioactive materials are removed only by radioactive decay and surface deposition. The rate of change in concentrations with time can then be written as the following set of seven simultaneous differential equations.

$$\frac{dR}{dt} = S_R - \lambda_R R$$

$$\frac{dAf}{dt} = \lambda_R . R - (\lambda_A + X + Q_F)\, Af$$

$$\frac{dAa}{dt} = XAf - (\lambda_A + Q_A)\, Aa$$

$$\frac{dBf}{dt} = \lambda_A\, (Af + pAa) - (\lambda_B + X + Q_F)\, Bf$$

$$\frac{dBa}{dt} = \lambda_A\, (1-p)Aa + XBf - (\lambda_B + Q_A)\, Ba$$

$$\frac{dCf}{dt} = \lambda_B Bf - (\lambda_C + X + Q_F)\, Cf$$

$$\frac{dCa}{dt} = \lambda_B Ba + XCf - (\lambda_C + Q_A)\, Ca$$

where R, A, B and C indicate the concentrations of Radon, RaA, RaB, RaC respectively, f, a indicate the free and attached forms of each daughter, and λ_R, λ_A, λ_B, λ_C are the respective decay constants. The radon supply

INTRODUCTION

The concentration of radon, thoron, and their daughters in mine air at any point depends on the past history of the air in moving from the surface to that point. The growth of radon and daughters in air moving down a tunnel was first presented by Schroeder and Evans, who derived a single analytic solution for the growth of WL under the assumptions that the release rate of radon per limit area of the tunnel surfaces was constant, there was no removal of daughters, and that transit times did not exceed 40 minutes. This approach can be extended to mine tunnel networks, but it provides only an upper limit to WL, and does not treat the growth of thoron and its daughters.

A general treatment of radionuclide growth with time in tunnel air requires solution of two sets of simultaneous equations, representing the changes in the concentration of radon, and the free and attached forms of its three daughters; thoron, and the free and attached forms of its two longer lived daughters; and of the attachment rate to the atmospheric aerosol.

The amount of calculation required to do this requires the use of computer modelling methods.

PROGRAM DESCRIPTION

General

Air flow in a mine tunnel can be idealized to either 'plug' flow, where the air moves down the tunnel with a minimum of longitudinal mixing, but with good lateral mixing (the Schroeder-Evans model); or a mixing flow where major longitudinal mixing takes place. Examples of this are the mixing zone downstream of junctions, and in the vicinity of mine equipment.

rate is given by S_R, X is the attachment rate of free daughters to the atmospheric aerosol, and Q_F, Q_A are the removal rates for free and attached daughters. The fraction of attached daughters that escape from the host particle as a result of alpha decay is 'p', taken equal to 0.83.

Attached daughters are removed by processes that remove the aerosol particles to which they are attached. The attachment rate X is set by the concentration of aerosol particles, and is therefore affected by the removal rate of attached daughters. An eighth simultaneous equation is therefore required to complete the set.

$$\frac{dX}{dt} = S_X - XQ_A$$

where S_X is the rate of increase in attachment rate due to particulate generation, and Q_A is the removal rate of attached daughters.

Similar equations can be written for thoron and its daughters:

$$\frac{dT}{dt} = S_T - \lambda_T T$$

$$\frac{dBf}{dt} = \lambda_T T - (\lambda_B + X + Q_F)\, Bf$$

$$\frac{dBa}{dt} = XBf - (\lambda_B + Q_A)\, Ba$$

$$\frac{dCf}{dt} = \lambda_B Bf - (\lambda_C + X + Q_F)\, Cf$$

$$\frac{dCa}{dt} = \lambda_B Ba + XCf - (\lambda_C + Q_A)\, Ca$$

where T, B, C indicate the concentrations of Thoron, ThB, ThC respectively, f, a indicate the free and attached forms of each daughter, and λ_T, λ_B, λ_C are the respective decay constants. The thoron supply rate is given by S_T,

and the other parameters have the same meaning as for radon daughters.

Given these equations, and knowledge of initial concentrations plus the supply and removal rates, the concentration of each nuclide at any time thereafter can be calculated by Runge-Kutta or other methods with high numerical precision. The uncertainties in the estimated concentrations depend only on the uncertainties in the values of the supply and removal rates.

If we have a tunnel segment over which conditions are essentially constant, the airflow rates and tunnel dimensions can be used to transform distances into travel times. The change of concentrations in a plug of air traversing the tunnel segment can then be calculated as shown above.

MIXING ZONES

When tunnels join, or near mining equipment, there can be zones of longitudinal mixing, where the treatment given above does not apply. In this case the airborne materials are removed from the zone by radioactive decay, surface deposition, and by the airstream passing through the zone. The rate of change of concentration in the zone can be expressed by a modified set of differential equations that incorporate a ventilation term. As we compute steady state conditions only in this program, we can go directly to the steady state solutions of the equations, obtained by putting $\frac{dC}{dt} = 0$.

The solutions for radon and its daughters are:

$$R = \frac{VR' + Sr}{(\lambda_R + V)}$$

$$Af = \frac{V.A'f + \lambda_R R}{(\lambda_A + V + X + Q_F)}$$

$$Aa = \frac{V.A'af + XAf}{\lambda_A + V + Q_A}$$

$$Bf = \frac{V.B'f + \lambda_A\,(Af + pAa)}{\lambda_B + V + X + Q_F}$$

$$Ba = \frac{V.B'a + \lambda_A\,(1-p)Aa + XBf}{\lambda_B + V + Q_A}$$

$$Cf = \frac{V.C'f + \lambda_B Bf}{\lambda_C + V + X + Q_F}$$

$$Ca = \frac{V.C'a + \lambda_B Ba + XCf}{\lambda_C + V + Q_A}$$

where R, A, B, C are the average concentrations of Radon, RaA, RaB, RaC respectively in the mixing zone - equal to the concentrations in the air leaving the zone, R', A', B', C' are the concentrations in the air entering the zone, V is the effective ventilation rate of the zone, and all other parameters are as before. Similar equations can be written for thoron and its daughters.

A mixing zone is required downstream of all junctions. The supply rate of radon, thoron and daughters into the zone is calculated as the volume weighted average of the air volumes and concentrations leaving the upstream segments.

NETWORK SOLUTION

As the change in concentration over any tunnel segment can be calculated, concentrations are obtained for the entire tunnel network by starting

at a point for which concentrations are known, and calculating the concentrations downstream. The solutions propagate through the tunnel network with the airflows. This is repeated until the concentrations are known for all tunnel segments. This technique will not work if there are recirculating networks, where the concentrations at an upstream junction depend on the concentrations downstream. That case requires an iterative solution, which this program does not supply.

FLOW CHART

A flow chart for the program is given in Table 1. The program is written in Fortran 77, and will run on a PDP 11/34 in less than 10K words memory with the present size of arrays. A program listing is provided.

PROGRAM VERIFICATION

The correct operation of the program was verified by computing the increase in radon daughter concentrations with time of a plug of radon passing through a network. Analytical solutions are available for that case if decay is the only removal mechanism. Exact agreement was obtained between the numerical results for that case with the analytical solutions. The results for the mixing zone segments were verified by hand calculation for standard cases.

PROGRAM OPERATION

To use the program, the mine tunnel network is divided into segments, over which size, emanation rate, airflow, and the release of particulates is essentially constant. The segments are given a numbered node at each end. No more than three tunnels can join at one node (See Figure 1).

The data for each segment is then entered into the computer, which automatically numbers the segments in their order of entry, echo checks the input data, and calculates the concentrations at the end of each segment. The initial and final concentrations for each segment are listed in segment order.

Data Entry

The program will accept data either from a terminal or a card reader. The data required is prompted from the terminal. Examples of a data entry session is shown in Figure 2 with comments. The data entered is echoed back, together with the calculated values of input and removal rates on a unit volume basis for the segment as shown in Figure 3.

Presentation of Data

The change in radionuclide concentrations over the length of the segment is then calculated, and listed in segment order at the start and end of each segment as shown in Figure 4. Output routines are provided in the program to print the results at time intervals for each plug flow segment if required. The concentrations at a junction are determined by averaging the volume weighted exit concentrations of the two supply segments.

TECHNICAL DETAILS

Subroutine New

This selects the segment to be calculated, and sets the initial concentrations at the entrance to the segment. A check array ICK is used to keep track of the status of each segment.

If ICK(I,1) = 1, the initial values of radon, thoron, daughter concentrations and attachment rate for segment I stored in array SY(I,*) are known;

ICK(I,2) = 1, the final values for segment I stored in array RY(I,*) are known.

The subroutine steps through the array, and skips all segments that have been completed (ICK(I,2) = 1). If only the initial values are known (ICKI,1) = 1), the subroutine returns the index number of that segment (NNEW) so the exit concentrations can be calculated. When a segment with no known initial values is found, the array (NODE (*,2) is searched to find the index numbers of the segments with exit node numbers equal to the segment entry node number in NODE (I,1). If the exit concentrations of these segments are not known, i.e. ICK(*,2) = 0, the program proceeds to the next segment. If there is only one segment (J) with known exit concentrations (ICK(J,2) = 1), these are copied from RY(J,*) into SY(I,*). If there are two upstream segments, then the node is a junction, the RY values are weighted by the airflows to produce an average concentration that is entered into SY(I,*). The subroutine returns the index number of the segment to be calculated (NNEW). If all segments have been calculated, NNEW is set to 0 so that the run can be terminated.

Subroutine SET

The parameters needed to calculate the exit concentrations from the input concentrations for segment I are stored in arrays S(I,*), SY(I,*). These values are copied from the arrays into the named dummy variables needed for the computation subroutines.

Subroutine RKGS

This solves the simultaneous differential equations for changes in radon, thoron, daughters and attachment rate (given in differential form in subroutine FCT) by a modified IBM scientific subroutine RKGS. It differs in that the time step over which the equations are evaluated is automatically modified to obtain a given level of accuracy. The initial value of the time step is set equal to the time interval at which the results are to be printed (by subroutine OUTP which is normally disabled), but the results are compared with those using a time step one half the size. If any result at the larger time step is negative, or the fractional difference between the results is larger than the value in PRMT(4), the smaller time step is used. If the average fractional difference of all results is less than 0.02 x PRMT(4), the calculations are repeated with a time step twice as large as that currently in use, and compared. If the error criteria are met, the larger time step is used. The upper limit on the time step is the time interval at which results are to be printed.

The initial segment values are given in array Y, and are updated at each time step, so the exit values also appear in array Y. Array RY holds exit values for each segment. The program copies Y into RY(I,*).

Subroutine VENT

This calculates the steady state values of radon, thoron, daughters and attachment rate for mixing segments, and is activated in preference to RKGS if ICK(I,3) = 2. The initial segment values are given in array Y, and exit values appear in array YO. The program copies YO into RY(I,*). A routine PRINT is provided to print the results of VENT, but is normally disabled.

Subroutine FPRINT

This prints in segment order the entry and exit nodes and the concentrations at each node.

Model Validation

The validity of the modelling procedure and the parameters derived in section 6 of the main report is shown by calculating the steady state concentrations in a tunnel network resembling the raise, slusher bench, and cut-out, during drilling with compressed air ventilation and with auxiliary ventilation, and comparing them with the values observed in the study. Figure 1 shows a sketch of the situation and the node model used for the calculations, and Table 2 lists the input data for each segment.

For comparison with measured values, the first set of computations are for a raise 58 m long (approximately the average length of the raises during the program). Table 3A shows the calculated values, and the range of values measured at similar locations. Good agreement is obtained. Measured values tend to be lower, as a result of additional dilutions not computed here. With the low air velocities in the raise when compressed air ventilation was in use, even passage of the measurement team up and down the raise would tend to decrease concentrations near the mouth.

The calculated change in WL from face to raise entrance, and the increase in WL at the slusher bench due to recirculation of ventilation air in the cut-out are comparable to those observed at the site.

Model Predictions

The change in length of the raise during the measurement period was minor, so it was not possible to measure the effect of a change in length on concentrations. The program was used to calculate this. Table 3B shows the range of concentrations expected as a raise is increased in length from 15 m - a newly started raise to 83 m - a nearly completed pilot raise. These would be the lowest concentrations expected, as the mine air then was generally higher than 0.14 WL(R). The range of calculated values is comparable to the lower values reported in the 1950's and indicates that part of the reason for the variability of those results was that measurements were taken in different lengths of raise, and probably in different locations.

TABLE 1

'MINES' FLOW CHART

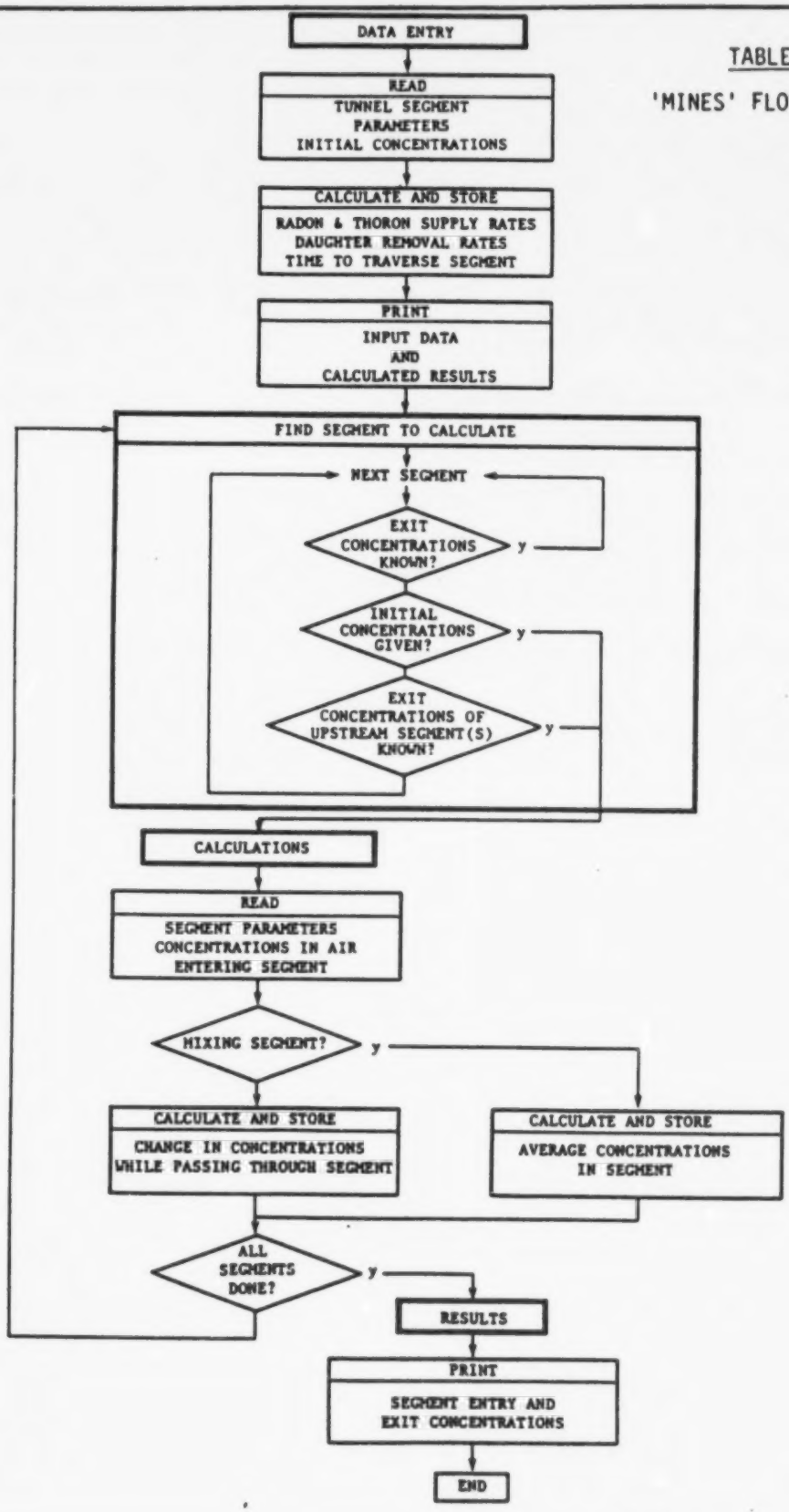


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TABLE 2

MINES Input Data

Segment Descriptions		Nodes
Cut-out	- Volume 306 m^3 Effective area 101 m^2	6,7
	Effective cross-section 30.6 m^2	
	Perimeter 10.1 m^2 Length 10 m	
	Ventilation 20 m^3/min mine air (recirculating)	
Slusher Bench	- Volume 178 m^3 Effective area 132 m^2	7,5
	Effective cross-section 17.8 m^2	
	Perimeter 13.2 m^2 Length 10 m	
	Ventilation 10 m^3/min cut-out air + raise air (recirculating)	
Raise	- Cross-section 4.5 m^2	5,4
	Perimeter 9 m Length 15, 50, 75 m	
	Ventilation - Auxiliary air + drill air (plug flow)	
Face	- Cross-section 4.5 m^2 Area 77 m^2	3,4
	Length 8 m	
	Ventilation - Auxiliary air + compressed air (recirculating)	

Input Airflows		
Auxiliary ventilation	- 30 m^3/min mine air	3,2
Compressed air	- 4 m^3/min	3,1
Cut-out ventilation	- 20 m^3/min mine air	6

TABLE 3

MODEL CALCULATIONS WITH 'MINES'

A - COMPARISON WITH MEASUREMENTS

Mine air 0.2 WL(R), 0.12 WL(T)

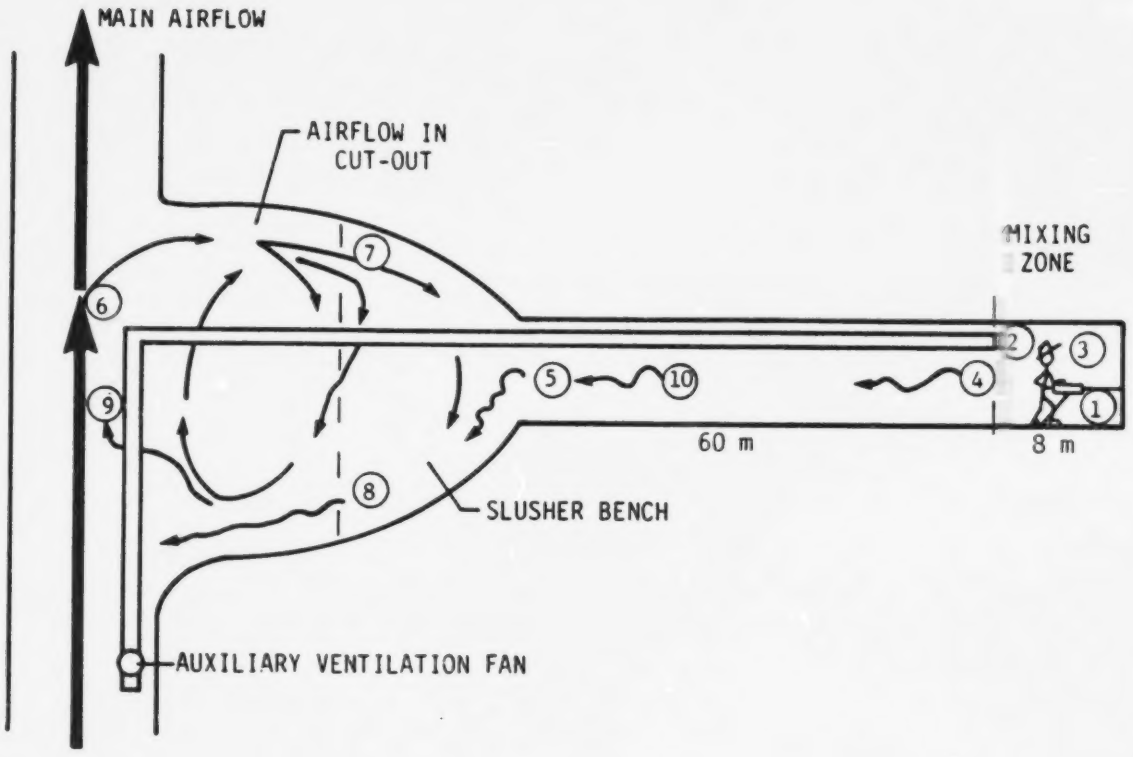
Conditions		LOCATIONS		
		Face	15 m from Mouth	Slusher Bench
Calculated:				
Auxiliary ventilation + drill air	WL(R)	0.11	0.12	0.15
	WL(T)	0.11	0.13	0.15
Observed:				
Auxiliary ventilation + drill air	WL(R)	0.12	0.14	0.16
	WL(T)	0.12	--	0.15
Calculated:				
Drill air + compressed air	WL(R)	0.02	0.17	0.31
	WL(T)	0.02	0.14	0.20
Observed:				
Drill air + compressed air	WL(R)	0.02-0.04	0.15-0.22	0.2-0.3
	WL(T)	0.02-0.04	0.09-0.13	0.1-0.2

B - CALCULATED CONCENTRATIONS FOR DIFFERENT CONDITIONS

Drill air + compressed air ventilation; Mine air 0.12 WL(R), 0.12 WL(T)

Raise Length		LOCATIONS		
		Face	Mouth	Slusher Bench
15 m	WL(R)	0.02	0.05	0.18
	WL(T)	0.02	0.05	0.16
83 m	WL(R)	0.02	0.78	0.41
	WL(T)	0.02	0.26	0.22

PHYSICAL LAYOUT OF RAISE



NODE MODEL

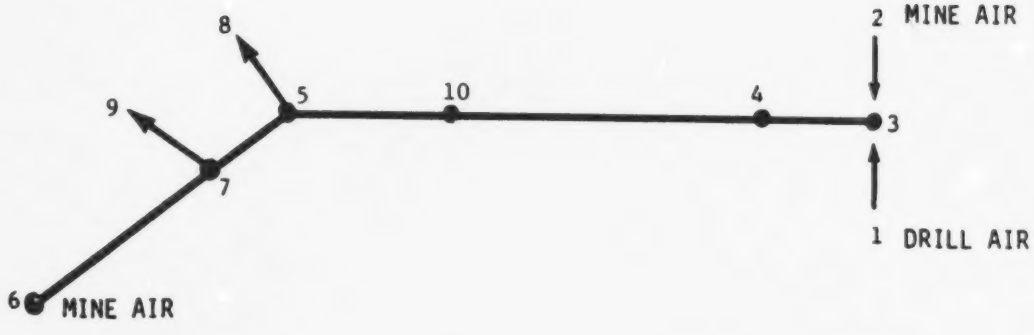


FIGURE 1 'MINES' EXAMPLE

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```
     ENTER IDENTIFIER
BLIND END INITIALLY FRESH AIR INTO ANAL.

      READ FROM CARDS?N

    ENTER TIME STEP (MIN)5.

  ENTER TUNNEL SEGMENT LNGTH,X-SECT.,PERIMETER
       FOLLOW WITH A CHARACTER FOR MIXING SEGMENT
100., 16.0, 20.0


  ENTER NODE NUMBERS
2,3


  ENTER RADON,THORON,SUPPLY RATE(PCI/M2/MIN)
0.2,0.3

  ENTER TOTAL INCREASE IN ATTACH. RATE(/MIN)
1.

  ENTER DEPOSITION VELOCITIES VF,VA (M/MIN)
0.3,.003

  INITIAL AIR CONDITIONS


  ENTER AIR QUANTITY(MT/MIN
400.

  ENTER RN,RAF,RAA,RIF,RBA,RACF,RACA(PCI/LITRE)      ENTER -1., 0., 0., 0., 0., 0., 0. IF
0.,0.,0.,0.,0.,0.                                     CONCENTRATIONS NOT FIXED

  ENTER ATTACHMENT RATE (/MIN)
1.

  ENTER TN,THBF,THBA,THCF,THCA(PCI/LITRE)
0.,0.,0.,0.,0.

    ENTER TIME STEP (MIN)5.                          ENTER -1. TO TERMINATE SESSION

  ENTER TUNNEL SEGMENT LNGTH,X-SECT.,PERIMETER
       FOLLOW WITH A CHARACTER FOR MIXING SEGMENT
```

FIGURE 2

TERMINAL ENTRY SESSION EXAMPLE

SEGMENT # 1 AIR FLOWS FROM NODE 2 TO NODE 3

TUNNEL SEGMENT LENGTH 100.0M A-AREA 16.0M2 PERIMETER 20.0M

AIR VOLUME 400.00000 M3/MIN RADON RELEASE RATE 660.00 PCI/M2/MIN THORON RELEASE RATE2000.00 PCI/M2/MIN
INCREASE IN ATTACHMENT 1.000 DEPOSITION VELOCITIES,FREE= 0.300M/MIN. ATTACHED= 0.003M/MIN

INITIAL CONDITIONS

RADON	RA-A(F)	RA-A(A)	RA-B(F)	RA-B(A)	RA-C(F)	RA-C(A)
0.000	0.000	0.000	0.000	0.000	0.000	0.000

THORON	TH-B(F)	TH-B(A)	TH-C(F)	TH-C(A)
0.000	0.000	0.000	0.000	0.000

TOTAL SUPPLY RATES RADON= 0.83 THORON= 3.25 PCI/MIN.M3
REMOVAL RATES FREE=0.37500 ATTACHED=0.00375 ATTACHMENT RATE= 1.00 PER MINUTE
RATE OF INCREASE IN ATTACHMENT = 0.00063 (/MIN.M3)
AIR VELOCITY 25.000 METERS/MIN

FIGURE 3

BLIND END INITIALLY FRESH AIR INTO AREA

FINAL RESULTS LISTED BY SEGMENT NUMBER

SEGMNT NODE	#		RADON	RAA-F	RAA-A	RAB-F	RAB-A	RAC-TOT	WL-RN	THORON	THB-F	THB-A	THC-F	THC-A	WL-TN	F	XO
1	2	IN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.000	1.00
	3	OUT	3.299	0.397	0.531	0.012	0.017	0.001	0.001	4.058	0.003	0.007	0.000	0.000	0.001	.033	0.99
2	3	IN	3.299	0.397	0.531	0.012	0.017	0.001	0.001	4.058	0.003	0.007	0.000	0.000	0.001	.033	0.99
	4	OUT	3.298	0.313	0.883	0.012	0.048	0.004	0.002	0.602	0.000	0.010	0.000	0.000	0.001	.047	0.96
3	4	IN	3.298	0.313	0.883	0.012	0.048	0.004	0.002	0.602	0.000	0.010	0.000	0.000	0.001	.047	0.96
	5	OUT	52.798	7.510	22.894	0.505	0.478	4.698	0.094	6.206	0.005	0.130	0.001	0.023	0.017	.179	0.78
4	5	IN	52.798	7.510	22.894	0.505	0.478	4.698	0.094	6.206	0.005	0.130	0.001	0.023	0.017	.179	0.78
	6	OUT	247.762	44.000	89.991	2.920	48.841	30.619	0.544	6.389	0.007	0.390	0.004	0.122	0.050	.220	0.48
5	3	IN	3.299	0.397	0.531	0.012	0.017	0.001	0.001	4.058	0.003	0.007	0.000	0.000	0.001	.033	0.99
	6	OUT	3.433	0.416	0.576	0.013	0.019	0.001	0.001	4.080	0.003	0.007	0.000	0.000	0.001	.035	0.99
6	6	IN	5.876	0.852	1.470	0.042	0.507	0.387	0.007	4.103	0.003	0.011	0.000	0.001	0.002	.113	0.98
	7	OUT	6.008	0.853	1.547	0.042	0.512	0.388	0.007	4.120	0.003	0.012	0.000	0.001	0.002	.112	0.99
7	7	IN	6.008	0.853	1.547	0.042	0.512	0.388	0.007	4.120	0.003	0.012	0.000	0.001	0.002	.112	0.99
	8	OUT	9.304	1.264	3.343	0.071	0.888	0.414	0.010	4.253	0.003	0.025	0.000	0.002	0.003	.109	0.97

FIGURE 4

```
C                    'MINES'
C                A RADON AND THORON DAUGHTERS PROGRAM
C                FOR MINE TUNNELS
C                      BY A.G.SCOTT--DSMA ATCON
C                           4195 DUNDAS ST. W
C                           TORONTO,ONT
C                                M8X 1Y4
C
C
0001          IMPLICIT REAL*8 (A-H,O-Z)
0002            COMMON NODE(10,2),ICK(10,3),S(10,17),SY(10,13),RY(10,13)
0003          DIMENSION PRMT(5),TNP(3),YT(6),YR(13),YO(13),DERY(13),AUX(13,13)
0004          COMMON /FCTB/ RS,TS,QA,QF,V,XS,VEL,TST
C                   DEFAULT VALUE FOR ACCURACY TEST=3% - PRMT(4)
0005          DATA PRMT /0.0,0.0,0.0,.03,0.0/
0006            BYTE DENT(40)
C
C
C
0007            NPAGE=0
0008          IW=1
0009          IT=2
0010            NS=0
0011          OPEN(UNIT=IW,NAME='LB0:VENT.LST',DISPOSE='PRINT',STATUS='NEW')
0012          OPEN(UNIT=IT,NAME='TI:',STATUS='UNKNOWN')
0013            OPEN(UNIT=3,NAME='CR0:',STATUS='UNKNOWN')
0014           40   FORMAT('       ENTER IDENTIFIER')
0015                WRITE(2,40)
0016                READ(2,41) DENT
0017           41   FORMAT(40A1)
0018           87   FORMAT(/,'$       READ FROM CARDS?')
0019                WRITE(2,87)
0020           85   FORMAT(A1)
0021                READ(2,85)IA
0022          998   IF(IA.NE.'Y') GO TO 881
0023                IT=3
0024                WRITE(2,88)
0025                READ(IT,*,END=999) TST
0026                GO TO 882
0027           88   FORMAT(/,'$    ENTER TIME STEP (MIN)')
0028          881   WRITE(2,88)
0029                READ(2,*) TST
0030                IF(TST.LT.0.) GO TO 999
0031           90   FORMAT(/,'    ENTER TUNNEL SEGMENT LNGTH,X-SECT.,PERIMETER'
                1   ,/,'          FOLLOW WITH A CHARACTER FOR MIXING SEGMENT')
0032          882   WRITE(2,90)
0033          883   FORMAT(3F10.1,1A1)
0034                READ (IT,883) TNP,ITYP
0035           80   FORMAT(//'    ENTER NODE NUMBERS')
0036                WRITE(2,80)
0037                READ(IT,*)N1,N2
0038           92   FORMAT(//'    ENTER RADON,THORON,SUPPLY RATE(PCI/M2/MIN)')
0039                WRITE(2,92)
0040                READ(IT,*) SR,ST
0041           93   FORMAT(/'    ENTER TOTAL INCREASE IN ATTACH. RATE(/MIN)')
```

```
0042            WRITE(2,93)
0043            READ(IT,*) XIN
0044       94   FORMAT(/'   ENTER DEPOSITION VELOCITIES VF,VA (M/MIN)')
0045            WRITE(2,94)
0046            READ(IT,*)VF,VA
0047       95   FORMAT(/'   INITIAL AIR CONDITIONS')
0048            WRITE(2,95)
0049       91   FORMAT(//'   ENTER AIR QUANTITY(M3/MIN)')
0050            WRITE(2,91)
0051            READ(IT,*) Q
0052       96   FORMAT(/'   ENTER RN,RAF,RAA,RBF,RBA,RACF,RACA(PCI/LITRE)')
0053            WRITE(2,96)
0054            READ(IT,*)YR(1),YR(2),YR(3),YR(4),YR(5),YR(6),YR(7)
0055            WRITE(2,105)
0056      105   FORMAT(/'   ENTER ATTACHMENT RATE (/MIN)')
0057            READ(IT,*) YR(8)
0058       97   FORMAT(/'   ENTER TN,THBF,THBA,THCF,THCA(PCI/LITRE)')
0059            WRITE(2,97)
0060            READ (IT,*) YR(9),YR(10),YR(11),YR(12),YR(13)
          C
          C                 ECHO CHECK
0061            NS=NS+1
0062            WRITE(1,68)NS,N1,N2
0063            NODE(NS,1)=N1
0064            NODE(NS,2)=N2
0065            ICK(NS,2)=0
0066            ICK(NS,1)=1
0067            ICK(NS,3)=0
0068            IF(ITYP.NE.' ') ICK(NS,3)=2
0069            IF(ITYP.NE.' ') WRITE(1,60)
0070       60   FORMAT(//,T25,'MIXING SEGMENT')
0071            JFL=0
          C   NEGATIVE RADON CONC. MEANS VALUES UNDEFINED
0072            IF(YR(1).GE.0.) GO TO 141
0073            ICK(NS,1)=0
0074            DO 140 J=1,13
0075      140   YR(J)=0.
0076            JFL=1
0077      141   CONTINUE
0078       86   FORMAT('1',//,T5,'SEGMENT #',I2,T25,'NODES',2(I5,3X))
0079       98   FORMAT(/,T20,'TUNNEL SEGMENT LENGTH',F10.1,'M',T60,
                1  'X-AREA',F10.1,'M2',T85,'PERIMETER',F10.1,'M')
0080            WRITE(1,98) TNP
0081            DO 202 I=1,3
0082      202   S(NS,I)=TNP(I)
0083       99   FORMAT(/,T15,'AIR VOLUME',F10.5,' M3/MIN',T45,'RADON RELEASE',
                1  ' RATE',F7.2,'  PCI/M2/MIN',T85,'THORON RELEASE RATE',F7.2,
                2  '  PCI/M2/MIN')
0084            WRITE(1,99) Q,SR,ST
0085            S(NS,4)=Q
0086            S(NS,5)=SR
0087            S(NS,6)=ST
0088      100   FORMAT(T3,'INCREASE IN ATTACHMENT',F10.3,T47,'DEPOSITION'
                1  ,' VELOCITIES,FREE=',F10.3,'M/MIN.   ATTACHED=',F10.3,'M/MIN')
0089            WRITE(1,100) XIN,VF,VA
```

```
0090            S(NS,7)=DG
0091            S(NS,8)=VF
0092            S(NS,9)=VA
0093      101   FORMAT(/,T20,'INITIAL CONDITIONS')
0094            WRITE(1,101)
0095            IF(JFL.EQ.1) WRITE(1,130)
0096      130   FORMAT(T20,'INITIAL VALUES UNDEFINED')
0097      102   FORMAT(/,T5,'RADON',T15,'RA-A(F)',T25,'RA-A(A)',T35,'RA-B(F)',
                1 T45,'RA-B(A)',T55,'RA-C(F)',T65,'RA-C(A)')
0098      104   FORMAT(//,T5,'THORON',T15,'TH-B(F)',T25,'TH-B(A)',T35,'TH-C(F)'
                1 T45,'TH-C(A)')

0099            WRITE(1,102)
0100      103   FORMAT(/,T2,7F10.3)
0101            WRITE(1,103) (YR(K),K=1,7)
0102            DO 203 I=1,7
0103      203   SY(NS,I)=YR(I)
0104            WRITE(1,104)
0105            WRITE(1,103) (YR(K),K=9,13)
0106            DO 204 I=9,13
0107      204   SY(NS,I)=YR(I)
        C TRANSFORM INPUT DATA
0108            QF=VF*TNP(3)/TNP(2)
0109            QA=VA*TNP(3)/TNP(2)
0110            VEL=Q/TNP(2)
        C               CONVERT CONC. TO PCI/L FROM M3
0111            RS=.001*SR*TNP(3)/TNP(2)
0112            TS=.001*ST*TNP(3)/TNP(2)
0113            SY(NS,8)=YR(8)
0114            XS=XIN/(TNP(1)*TNP(2))
0115            S(NS,17)=XS
0116            WRITE(1,121) RS,TS
0117            S(NS,10)=RS
0118            S(NS,11)=TS
0119      121   FORMAT(//,T10,'TOTAL SUPPLY RATES  RADON=',F7.2,
                1 '   THORON=',F7.2,' PCI/MIN,M3')
0120            WRITE(1,122)QF,QA,YR(8),XS
0121            S(NS,12)=QF
0122            S(NS,13)=QA
0123      122   FORMAT(T10,'REMOVAL RATES FREE=',F7.5,' ATTACHED=',F7.5,
                1 '  ATTACHMENT RATE=',F7.2,'   PER MINUTE',/,T35,
                2 'RATE OF INCREASE IN ATTACHMENT = ',F7.5,' (/MIN,M3)')
0124            WRITE(1,123) VEL
0125            S(NS,14)=VEL
0126            S(NS,15)=TST
0127      123   FORMAT(T10,'AIR VELOCITY',F7.3,' METERS/MIN')
0128            V=Q/(TNP(1)*TNP(2))
0129            S(NS,16)=V
0130            IF(TNP(2).LT.(3*TNP(1)*TNP(1))) GO TO 125
0131            IF(ICK(NS,3).EQ.0) WRITE(1,124)
0132      124   FORMAT(//,T20,'SEGMENT TOO SHORT,SHOULD BE VENT TYPE')
0133      125   CONTINUE
0134            GO TO 998
        C               END OF DATA INPUT SECTION
0135      999   NDIMR=13
```

```
      D     WRITE(1,*) ICK,NODE
      C                RETURN TO HERE FOR CALCULATION
0136    940   CALL NEW(NNEW,NS)
0137          IF(NNEW.EQ.0) GO TO 950
0138          CALL SET(NNEW,PRMT,YR,NDIMR,DERY)
0139     68   FORMAT('1',///,T20,'SEGMENT #',I3,T40,'AIR FLOWS FROM NODE',
     1        I4,' TO NODE',I3)
      C       WRITE(1,68)  NNEW,NODE(NNEW,1),NODE(NNEW,2)
0140          IF(ICK(NNEW,3).NE.2) GO TO 941
0141          CALL VENT(YR,NDIMR,YO)
0142          CALL PRINT(YR,YO,NDIMR)
0143          DO 992 J=1,13
0144    992   RY(NNEW,J)=YO(J)
0145          ICK(NNEW,2)=1
0146          GO TO 940
0147    941   CALL RKGS(PRMT,YR,DERY,NDIMR,THLF,AUX)
0148    942   DO 991 J=1,13
0149    991   RY(NNEW,J)=YR(J)
0150          ICK(NNEW,2)=1
0151          GO TO 940
0152    950   WRITE(2,951)
0153    951   FORMAT('     ALL DONE')
0154          CALL FPRINT(NS,DENT)
0155    962   STOP
0156          END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	003704	994	RO,I,CON,LCL
$PDATA	003036	783	RO,D,CON,LCL
$IDATA	000020	8	RW,D,CON,LCL
$VARS	003556	951	RW,D,CON,LCL
$TEMPS	000002	1	RW,D,CON,LCL
.$$$$.	006724	1770	RW,D,OVR,GBL,,SAV
FCTB	000100	32	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 021566 4539

```
0001              SUBROUTINE NEW(NNEW,NS)
0002            IMPLICIT REAL*8 (A-H,O-Z)
0003              COMMON NODE(10,2),ICK(10,3),S(10,17),SY(10,13),RY(10,13)
0004              IT=0
0005              DO 99 I=1,NS
0006              IT=IT+ICK(I,2)
0007         99   CONTINUE
           D      WRITE(1,*) IT
0008              IF(IT.GT.NS) GO TO 199
           C HERE IF ALL SEGS CALC
0009              NNEW=0
0010              RETURN
0011         199  DO 98 J=1,NS
           C  SKIP DONE SEGS
0012              IF(ICK(J,2).EQ.1) GO TO 98
           C    CHK FOR INIT. VAL
0013              IF(ICK(J,1).EQ.1) GO TO 198
           C    LOOK FOR PREV. SEG.
0014              NP=0
0015              DO 100 K=1,NS
0016              IF(NODE(K,2).NE.NODE(J,1)) GO TO 100
           C  MATCH FOUND
0017              NN=NP
0018              NP=K
           D      WRITE(1,*) NN,NP,K,J
0019         100  CONTINUE
0020              IF(NN.NE.0) GO TO 202
0021              IF(NP.NE.0) GO TO 201
           C  HERE IF NO PREV SEG
           C  STSRT SEG
0022              NNEW=J
           D      WRITE(1,*) J
0023              RETURN
           C    COPY OVER VALUES FROM PREVIOS SEGMENT
0024         201  DO 299 L=1,13
0025         299  SY(J,L)=RY(NP,L)
           D      WRITE(1,*) J,L,NP
           D      WRITE(1,*) SY
0026              GO TO 198
           C    GET HERE IF JUNCTION
0027         202  IF((ICK(NP,2).EQ.1).AND.(ICK(NN,2).EQ.1)) GO TO 210
0028          98  CONTINUE
           C    GET HERE IF BOTH JUNCTS DONE
0029         210  DO 88 M=1,13
0030              SY(J,M)=(RY(NP,M)*S(NP,4)+ RY(NN,M)*S(NN,4))
0031              SY(J,M)=SY(J,M)/S(J,4)
0032          88  CONTINUE
           D      WRITE(1,*) NP,NN,J,M
           D      WRITE(1,*) SY
0033         198  NNEW=J
           D      WRITE(1,*) NNEW
0034              RETURN
0035              END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
SCODE1	000774	254	RO,I,CON,LCL
SVARS	000020	8	RW,D,CON,LCL
STEMPS	000010	4	RW,D,CON,LCL
.$$$$.	006724	1770	RW,D,OVR,GBL,SAV

TOTAL SPACE ALLOCATED = 007750 2036

```
0001            SUBROUTINE SET(NNEW,PRMT,Y,NDIMR,DERY)
0002          IMPLICIT REAL*8 (A-H,O-Z)
0003            COMMON NODE(10,2),ICK(10,3),S(10,17),SY(10,13),RY(10,13)
0004          COMMON /FCTB/ RS,TS,DA,DF,V,XS,VEL,TST
0005            DIMENSION DERY(NDIMR),PRMT(5),Y(13),YT(13)
0006      199 DO 10 I=1,NDIMR
0007       10   DERY(I)=1./FLOAT(NDIMR)
0008            I=NNEW
      D         WRITE(1,*)(S(I,K),K=1,16)
0009            RS=S(I,10)
0010            TS=S(I,11)
0011            DF=S(I,12)
0012            DA=S(I,13)
0013            VEL=S(I,14)
0014            TST=S(I,15)
0015            V=S(I,16)
0016            XS=S(I,17)
0017            PRMT(2)=S(I,1)/VEL
0018            PRMT(3)=TST
0019            PRMT(1)=0.
0020            DO 240  J=1,13
0021     240    Y(J)=SY(I,J)
0022     994    RETURN
0023            END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	000426	139	RO,I,CON,LCL
$IDATA	000044	18	RW,D,CON,LCL
$VARS	000154	54	RW,D,CON,LCL
$TEMPS	000002	1	RW,D,CON,LCL
.$$$$.	006724	1770	RW,D,OVR,GBL,SAV
FCTB	000100	32	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 007674 2014

```
0001          SUBROUTINE RKGS(PRMT,Y,DERY,NDIM,IHLF,AUX)
0002          IMPLICIT REAL*8 (A-H,O-Z)
0003          DIMENSION Y(NDIM),DERY(NDIM),AUX(13,NDIM),A(4),B(4),C(4),PRMT(5)
0004          DO 1 I=1,NDIM
0005        1 AUX(8,I)=.06666667*DERY(I)
0006          X=PRMT(1)
0007          XEND=PRMT(2)
0008          H=PRMT(3)
0009          PRMT(5)=0.
0010          CALL FCT(X,Y,NDIM,DERY,TNP)
              C     ERROR TEST
0011          IF(H*(XEND-X))38,37,2
              C     PREPARATIONS FOR RUNGE-KUTTA METHOD
0012        2 A(1)=.5
0013          A(2)=.2928932
0014          A(3)=1.707107
0015          A(4)=.1666667
0016          B(1)=2.
0017          B(2)=1.
0018          B(3)=1.
0019          B(4)=2.
0020          C(1)=.5
0021          C(2)=.2928932
0022          C(3)=1.707107
0023          C(4)=.5
              C     PREPARATIONS OF FIRST RUNGE-KUTTA STEP
0024          DO 3 I=1,NDIM
0025          AUX(1,I)=Y(I)
0026          AUX(2,I)=DERY(I)
0027          AUX(3,I)=0.
0028        3 AUX(6,I)=0.
0029          IREC=0
0030          H=H+H
0031          IHLF=-1
0032          ISTEP=0
0033          IEND=0
              C     START OF A RUNGE-KUTTA STEP
0034        4 IF((X+H-XEND)*H)7,6,5
0035        5 H=XEND-X
0036        6 IEND=1
              C     RECORDING OF INITIAL VALUES OF THIS STEP
0037        7 CALL OUTP(X,Y,DERY,IREC,NDIM,PRMT,H)
0038          IF(PRMT(5))40,8,40
0039        8 ITEST=0
0040        9 ISTEP=ISTEP+1
              C     START OF INNERMOST RUNGE-KUTTA LOOP
0041          J=1
0042       10 AJ=A(J)
0043          BJ=B(J)
0044          CJ=C(J)
0045          DO 11 I=1,NDIM
0046          R1=H*DERY(I)
0047          R2=AJ*(R1-BJ*AUX(6,I))
0048          Y(I)=Y(I)+R2
0049          R2=R2+R2+R2
```

```
0050          11 AUX(6,I)=AUX(6,I)+R2-CJ*R1
0051             IF(J-4)12,15,15
0052          12 J=J+1
0053             IF(J-3)13,14,13
0054          13 X=X+.5*H
0055          14 CALL FCT(X,Y,NDIM,DERY,TNP)
0056             GO TO 10
              C     END OF INNERMOST RUNGE-KUTTA LOOP
              C     TEST OF ACCURACY
0057          15 IF(ITEST)16,16,20
              C     IN CASE ITEST=0 THERE IS NO POSSIBILITY FOR TESTING OF ACCURACY
0058          16 DO 17 I=1,NDIM
0059          17 AUX(4,I)=Y(I)
0060             ITEST=1
0061             ISTEP=ISTEP+ISTEP-2
0062          18 IHLF=IHLF+1
0063             X=X-H
0064             H=.5*H
0065             DO 19 I=1,NDIM
0066             Y(I)=AUX(1,I)
0067             DERY(I)=AUX(2,I)
0068          19 AUX(6,I)=AUX(3,I)
0069             GO TO 9
              C     IN CASE ITEST=1 TESTING OF ACCURACY IS POSSIBLE
0070          20 IMOD=ISTEP/2
0071             IF(ISTEP-IMOD-IMOD)21,23,21
0072          21 CALL FCT(X,Y,NDIM,DERY,TNP)
0073             DO 22 I=1,NDIM
0074             AUX(5,I)=Y(I)
0075          22   AUX(7,I)=DERY(I)
0076             GO TO 9
              C     COMPUTATION OF TEST VALUE DELT
0077          23 DELT=0.
0078             IFLAG=0
0079             DO 24 I=1,NDIM
              C  24 DELT=DELT+AUX(8,I)*ABS(AUX(4,I)-Y(I))
0080               IF(Y(I)-1.E-6) 24,24,224
0081        224   D=ABS(AUX(4,I)/Y(I)-1.)
0082               IF(D.GT.PRMT(4)) IFLAG=1
              D     IF(D.GT.PRMT(4)) WRITE(1,*) I,D
0083          24   DELT=DELT+D
0084               DELT=DELT/NDIM
              D     WRITE(1,*) DELT,PRMT(4),H

0085        124   DO 125 I=1,NDIM
0086        125   IF(Y(I).LT.0.) GO TO 25
0087               IF(IFLAG.EQ.0) GO TO 28
              C     IF(DELT-PRMT(4))28,28,25
              C     ERROR IS TOO GREAT
0088          25 IF(IHLF-10)26,36,36
0089          26 DO 27 I=1,NDIM
0090          27 AUX(4,I)=AUX(5,I)
0091             ISTEP=ISTEP+ISTEP-4
0092             X=X-H
0093             IEND=0
```

```
0094            GO TO 18
          C     RESULT VALUES ARE GOOD
0095         28 CALL FCT(X,Y,NDIM,DERY,TNP)
0096            DO 29 I=1,NDIM
0097               AUX(1,I)=Y(I)
0098               AUX(2,I)=DERY(I)
0099               AUX(3,I)=AUX(6,I)
0100               Y(I)=AUX(5,I)
0101         29 DERY(I)=AUX(7,I)
0102            CALL OUTP(X-H,Y,DERY,IHLF,NDIM,PRMT,H)
0103            IF(PRMT(5))40,30,40
0104         30 DO 31 I=1,NDIM
0105            Y(I)=AUX(1,I)
0106         31 DERY(I)=AUX(2,I)
0107            IREC=IHLF
0108            IF(IEND)32,32,39
          C     INCREMENT GETS DOUBLED
0109         32 IHLF=IHLF-1
0110            ISTEP=ISTEP/2
0111            H=H+H
          D       WRITE(1,*)H
0112            IF(IHLF)4,33,33
0113         33 IMOD=ISTEP/2
0114            IF(ISTEP-IMOD-IMOD)4,34,4
0115         34 IF(DELT-.02*PRMT(4))35,35,4
0116         35 IHLF=IHLF-1
0117            ISTEP=ISTEP/2
0118            H=H+H
0119            GO TO 4
          C     RETURNS TO CALLING PROGRAM
0120         36 IHLF=11
0121            CALL FCT(X,Y,NDIM,DERY,TNP)
0122            GO TO 39
0123         37 IHLF=12
0124            GO TO 39
0125         38 IHLF=13
0126         39 CALL OUTP(X,Y,DERY,IHLF,NDIM,PRMT,H)
0127         40 RETURN
0128            END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	004012	1029	RO,I,CON,LCL
$PDATA	000060	24	RO,D,CON,LCL
$IDATA	000174	62	RW,D,CON,LCL
$VARS	000310	100	RW,D,CON,LCL
$TEMPS	000004	2	RW,D,CON,LCL

TOTAL SPACE ALLOCATED = 004602 1217

```
0001          SUBROUTINE OUTP(X,Y,DERY,IHLF,NDIM,PRMT,H)
0002          IMPLICIT REAL*8 (A-H,O-Z)
0003          COMMON /FCTB/ RS,TS,QA,QF,V,XS,VEL,TST
0004          DIMENSION Y(NDIM),DERY(NDIM),PRMT(5),W(7),WT(5),ZZ(13)
0005          DATA W/0.0,0.00103,0.00103,0.00507,0.00507,0.00373,0.00373/
0006            DATA WT/0.,.1223,.1223,.0116,.0116/
0007          IW=1
0008            DEL=.45*H
0009          IF(IHLF.LT.11)GO TO 9
0010          IF(IHLF.EQ.11)WRITE(IW,11)IHLF
0011          IF(IHLF.EQ.12)WRITE(IW,12)IHLF
0012          IF(IHLF.EQ.13)WRITE(IW,13)IHLF
0013       11 FORMAT(/,1X,'IHLF=',I5,5X,'   ERROR TOO GREAT WITHIN PERMITTED NU
             1 OF BISECTIONS')
0014       12 FORMAT(/,1X,'IHLF=',I5,5X,'INCREMENT ZERO OR LOWER LIMIT EQUALS U
             2PER LIMIT')
0015       13 FORMAT(/,1X,'IHLF=',I5,5X,'INCREMENT SIGN DIFFERS FROM SIGN OF (UI
             3PER LIMIT - LOWER LIMIT')
0016            PRMT(5)=IHLF
           C    GO TO 5
0017          9 NZ=INT(X/TST+0.5)
0018            Z=NZ
0019            Z=Z*TST
                IF(ABS(PRMT(2)-X)-ABS(DEL)) 4,4,15
0021       15 IF(ABS(Z-X)-ABS(DEL))4,5,5
0022        4 IF(X)5,1,2
0023        2 IF(NLINES-58)6,6,1
0024        1 WRITE(IW,1331)
0025        3 FORMAT('1',//,3X,'TIME    RADON   RAA-F   RAA-A   RAB-F   RAB-A
             3RAC-F   RAC-A     WL   EFACT     XZ     QF     QA  DIST  EFACT-A'
             4,/,2X,'(MIN) ',7(1X,'(PCI/L)'))
0026       31   FORMAT(//,'  TIME',T10,'DIST',T16,'RADON',T24,'RAA-F',T32,
             1  'RAA-A',T40,'RAB-F',T48,'RAB-A',T56,'RAC-TOT',T64,'WL-RN',T72,
             2  'THORON',T80,'THB-F',T88,'THB-A',T96,'THC-F',T104,'THC-A',T112,
             3  'WL-TN',T120,'F',T128,'XO')
0027     1331   FORMAT('1',////,T5,'  TIME',T16,'RAA-F',T24,
             1  'RAA-A',T32,'RAA-TOT',T40,'RAB-F',T48,'RAB-A',T56,
             1   'RAB-TOT',T64,'RAC-TOT',T72,'FPAE(R)',
             2  T80,'THB-F',T88,'THB-A',T96,'THB-TOT',T104,'THC-TOT',T112,
             3  'FPAE(T)')
0028          NLINES=4
0029        6 WL=0.0
0030          DO 7 I=1,7
0031          WL=WL+W(I)*Y(I)
0032        7 CONTINUE
0033          WLT=0.
0034          DO 17 I=1,5
0035       17   WLT=WLT+WT(I)*Y(I+8)
0036          IF (Y(1).EQ.0.)  GO TO 99
0037          IF((Y(2)+Y(3)).EQ.0.) GO TO 98
0038      100   EF=100.*WL/Y(1)
0039          EFA=100.0*WL/(Y(2)+Y(3))
0040          GO TO 101
0041       98   EFA=0.
0042       99   EF=0.
```

```
0043      101   CONTINUE
          C       WRITE(IW,8)X,(X*VEL),(Y(K),K=1,5),(Y(6)+Y(7)),WL,
          C     1 (Y(K),K=9,13),WLT,EF,Y(8)
0044        8 FORMAT(/,1X,F6.1,1X,F5.1,1X,13(F7.3,1X),F4.3,2X,F5.2)
0045          CORR=1000./Y(1)
0046          CORT=1000./Y(9)
0047          IF(Y(1).LT.1.) CORR=0.
0048          IF(Y(9).LT.0.1) CORT=0.
0049          DO 999 I=1,7
0050      999 ZZ(I)=CORR*Y(I)
0051          DO 998 I=9,13
0052      998 ZZ(I)=CORT*Y(I)
0053          FAR=EF
0054          FAT=WLT*13.6/Y(9)
0055          WRITE(IW,138)X,(ZZ(K),K=2,3),(ZZ(2)+ZZ(3)),ZZ(4),ZZ(5),
     1    (ZZ(4)+ZZ(5)),(ZZ(6)+ZZ(7)),
     1    FAR,(ZZ(K),K=10,11),(ZZ(10)+ZZ(11)),(ZZ(12)+ZZ(13)),FAT
0056      138 FORMAT(/,4X,F6.1,3X,8(F7.2,1X),
     1    T79,6(F7.2,1X),F7.3)
0057          NLINES=NLINES+2
0058        5 RETURN
0059          END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	001612	453	RO,I,CON,LCL
$PDATA	000644	210	RO,D,CON,LCL
$IDATA	000052	21	RW,D,CON,LCL
$VARS	000442	145	RW,D,CON,LCL
FCTB	000100	32	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 003272 861

```
0001          SUBROUTINE FCT(X,Y,NDIM,DERY,TNP)
0002          IMPLICIT REAL*8 (A-H,O-Z)
0003          DIMENSION Y(NDIM),DERY(NDIM)
0004          REAL*8 L0,L1,L2,L3
0005          COMMON /FCTB/ RS,TS,QA,QF,V,XS,VEL,TST
0006            L0=1.26E-4
0007            L1=2.27E-1
0008            L2=2.59E-2
0009            L3=3.52E-2
0010          R1=0.86
0011            T0=.763
0012            T1=.001089
0013            T2=.01145
              C  FOR TUNNELS,V=0
0014            V=0.
              C
0015          GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13),NDIM
0016       13   DERY(13)=T2*Y(11)+Y(8)*Y(12)-(T2+QA+V)*Y(13)
0017       12  DERY(12)=T2*Y(10)+T2*Y(11)-(T2+Y(8)+QF+V)*Y(12)
0018       11  DERY(11)=Y(8)*Y(10)-(T1+QA+V)*Y(11)
0019       10  DERY(10)=T1*Y(9)-(T1+Y(8)+QF+V)*Y(10)
0020        9 DERY(9)=-Y(9)*T0+TS
0021        8   DERY(8)=-Y(8)*QA+XS
0022        7 DERY(7)=L3*Y(5)+Y(8)*Y(6)-(L3+QA+V)*Y(7)
0023        6 DERY(6)=L3*Y(4)-(L3+Y(8)+QF+V)*Y(6)
0024        5 DERY(5)=L2*(1-R1)*Y(3)+Y(8)*Y(4)-(L2+QA+V)*Y(5)
0025        4 DERY(4)=L2*Y(2)+R1*L2*Y(3)-(L2+Y(8)+QF+V)*Y(4)
0026        3 DERY(3)=Y(8)*Y(2)-(L1+QA+V)*Y(3)
0027        2 DERY(2)=L1*Y(1)-(L1+Y(8)+QF+V)*Y(2)
0028        1 DERY(1)=-Y(1)*L0+RS
0029       99 RETURN
0030          END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	001362	377	RO,I,CON,LCL
$PDATA	000134	46	RO,D,CON,LCL
$IDATA	000040	16	RW,D,CON,LCL
$VARS	000100	32	RW,D,CON,LCL
FCTB	000100	32	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 001756 503

```
0001            SUBROUTINE VENT(Y,NDIM,YO)
                C   CALCULATES EQUILIBRIUM DAUGHTER CONCS
0002              IMPLICIT REAL*8 (A-H,O-Z)
0003              DIMENSION Y(NDIM),YO(NDIM)
0004              REAL*8 L0,L1,L2,L3
0005              COMMON /FCTB/ RS,TS,OA,OF,V,XS,VEL,TST
0006                L0=1.26E-4
0007                L1=2.27E-1
0008                L2=2.59E-2
0009                L3=3.52E-2
0010              R1=0.86
0011                T0=.763
0012                T1=.001089
0013                T2=.01145
0014                YO(8)=(V*Y(8)+XS)/(V+OA)
0015                YO(1)=(V*Y(1)+RS)/(V+L0)
0016                YO(2)=(V*Y(2)+YO(1)*L1)/(V+L1+YO(8)+OF)
0017                YO(3)=(V*Y(3)+YO(8)*YO(2))/(L1+V+OA)
0018                YO(4)=(V*Y(4)+L2*YO(2)+R1*L2*YO(3))/(L2+YO(8)+OF+V)
0019                YO(5)=(V*Y(5)+L2*(1-R1)*YO(3)+YO(8)*YO(4))/(L2+OA+V)
0020                YO(6)=(V*Y(6)+L3*YO(4))/(L3+YO(8)+OF+V)
0021                YO(7)=(V*Y(7)+L3*YO(5)+YO(8)*YO(6))/(L3+OA+V)
0022                YO(9)=(V*Y(9)+TS)/(V+T0)
0023                YO(10)=(V*Y(10)+T1*YO(9))/(T1+YO(8)+OF+V)
0024                YO(11)=(V*Y(11)+YO(8)*YO(10))/(T1+OA+V)
0025                YO(12)=(V*Y(12)+T2*YO(10)+T2*YO(11))/(T2+YO(8)+OF+V)
0026                YO(13)=(V*Y(13)+T2*YO(11)+YO(8)*YO(12))/(T2+OA+V)
0027                RETURN
0028                END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
SCODE1	001160	312	RO,I,CON,LCL
SPDATA	000100	32	RO,D,CON,LCL
SIDATA	000040	16	RW,D,CON,LCL
SVARS	000102	33	RW,D,CON,LCL
FCTB	000100	32	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 001522 425

```
0001            SUBROUTINE PRINT(Y,YO,NDIM)
0002           IMPLICIT REAL*8 (A-H,O-Z)
0003           COMMON /FCTR/ RS,TS,QA,QF,V,XS,VEL,TST
0004           DIMENSION Y(NDIM),PRMT(5),YO(13),W(7),WT(5)
0005           DATA W/0.0,0.00103,0.00103,0.00507,0.00507,0.00373,0.00373/
0006             DATA WT/0.,.1223,.1223,.0116,.0116/
0007             RETURN
0008           IW=1
F77 -- ERROR 26-W NO PATH TO THIS STATEMENT
                  IN MODULE PRINT AT LINE 8

0009             WRITE(IW,21)
0010        21   FORMAT(//,T20,'MIXING SEGMENT')
0011         1  WRITE(IW,31)
0012         3  FORMAT('1',//,3X,'          RADON    RAA-F    RAA-A    RAB-F    RAB-A
                3RAC-F    RAC-A     WL    EFACT     XZ      QF      QA   DIST  EFACT-A'
               4,/,2X,'(MIN) ',7(1X,'(PCI/L)'))
0013        31   FORMAT(//,                T16,'RADON',T24,'RAA-F',T32,
               1  'RAA-A',T40,'RAB-F',T48,'RAB-A',T56,'RAC-TOT',T64,'WL-RN',T72,
               2  'THORON',T80,'THB-F',T88,'THB-A',T96,'THC-F',T104,'THC-A',T112,
               3  'WL-TN',T120,'F',T128,'XO')
0014         6  WL=0.0
0015           DO 7 I=1,7
0016           WL=WL+W(I)*Y(I)
0017         7 CONTINUE
0018             WLT=0.
0019             DO 17 I=1,5
0020        17   WLT=WLT+WT(I)*Y(I+8)
0021             IF (Y(1).EQ.0.)  GO TO 99
0022             IF((Y(2)+Y(3)).EQ.0.) GO TO 98
0023       100   EF=100.*WL/Y(1)
0024           EFA=100.0*WL/(Y(2)+Y(3))
0025             GO TO 101
0026        98   EFA=0.
0027        99   EF=0.
0028       101   WRITE(IW,8)(Y(K),K=1,5),(Y(6)+Y(7)),WL,
                1  (Y(K),K=9,13),WLT,EF,Y(8)
0029         8 FORMAT(/,T15,13(F7.3,1X),F4.3,2X,F5.2)
0030           WL=0.0
0031           DO 77 I=1,7
0032           WL=WL+W(I)*YO(I)
0033        77  CONTINUE
0034             WLT=0.
0035             DO117 I=1,5
0036       117   WLT=WLT+WT(I)*YO(I+8)
0037             IF (YO(1).EQ.0.)  GO TO 199
0038             IF((YO(2)+YO(3)).EQ.0.) GO TO 198
0039             EF=100.*WL/YO(1)
0040           EFA=100.0*WL/(YO(2)+YO(3))
0041             GO TO 1101
0042       198   EFA=0.
0043       199   EF=0.
0044      1101   WRITE(IW,8)(YO(K),K=1,5),(YO(6)+YO(7)),WL,
                1  (YO(K),K=9,13),WLT,EF,YO(8)
0045         5 RETURN
```

```
0046          END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	001212	325	RO,I,CON,LCL
$PDATA	000262	89	RO,D,CON,LCL
$IDATA	000032	13	RW,D,CON,LCL
$VARS	000256	87	RW,D,CON,LCL
FCTB	000100	32	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 002104 546

F77 -- 1 ERRORS MINES.FTN;343

```
0001            SUBROUTINE FPRINT(NS,DENT)
0002          IMPLICIT REAL*8 (A-H,O-Z)
0003          COMMON /FCTB/ RS,TS,QA,QF,V,XS,VEL,TST
0004            COMMON NODE(10,2),ICK(10,3),S(10,17),SY(10,13),RY(10,13)
0005          DIMENSION Y(13),PRMT(5),W(7),WT(5)
0006            BYTE DENT(40)
0007          DATA W/0.0,0.00103,0.00103,0.00507,0.00507,0.00373,0.00373/
0008            DATA WT/0.,.1223,.1223,.0116,.0116/
0009          IW=1
0010         20   FORMAT('1',//,T25,40A1)
0011            WRITE(IW,20) DENT
0012            WRITE(IW,21)
0013         21   FORMAT(////,T20,'FINAL RESULTS LISTED BY SEGMENT NUMBER',///)
0014          1 WRITE(IW,31)
0015         31   FORMAT(//,'   SEGMNT #',     T16,'RADON',T24,'RAA-F',T32,
              1  'RAA-A',T40,'RAB-F',T48,'RAB-A',T56,'RAC-TOT',T64,'WL-RN',T72,
              2  'THORON',T80,'THB-F',T88,'THB-A',T96,'THC-F',T104,'THC-A',T112,
              3  'WL-TN',T120,'F',T126,'XO',/,T5,'NODE')
0016            DO 666 J=1,NS
0017            SHNT=0.
0018            DO 667 JJ=1,13
0019            Y(JJ)=SY(J,JJ)
0020        667   CONTINUE
0021          6 WL=0.0
0022            DO 7 I=1,7
0023            WL=WL+W(I)*Y(I)
0024          7 CONTINUE
0025            WLT=0.
0026            DO 17 I=1,5
0027         17   WLT=WLT+WT(I)*Y(I+8)
0028            IF (Y(1).EQ.0.)  GO TO 99
0029            IF((Y(2)+Y(3)).EQ.0.) GO TO 98
0030        100   EF=100.*WL/Y(1)
0031          EFA=100.0*WL/(Y(2)+Y(3))
0032            GO TO 101
0033         98   EFA=0.
0034         99   EF=0.
0035        101   IF(SHNT.GT.0.)GO TO777
0036            WRITE(IW,8) J,NODE(J,1),(Y(K),K=1,5),(Y(6)+Y(7)),WL,
              1  (Y(K),K=9,13),WLT,EF,Y(8)
0037          8   FORMAT(//,1X,I2,2X,I2,T10,' TN',T15,13(F7.3,1X)
              1  , F4.3,2X,F5.2,2X,I2)
0038        888   FORMAT(/,1X,6X,I2,T10,' OUT',T15,13(F7.3,1X),F4.3,2X,F5.2,4X,I2)
0039            DO 668 JJ=1,13
0040            Y(JJ)=RY(J,JJ)
0041        668   CONTINUE
0042            SHNT=1.
0043            GO TO 6
0044        777   WRITE(IW,888)NODE(J,2),(Y(K),K=1,5),(Y(6)+Y(7)),WL,
              1  (Y(K),K=9,13),WLT,EF,Y(8)
0045            SHNT=0.
0046        666   CONTINUE
0047          5 RETURN
0048            END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
SCODE1	001402	385	RO,I,CON,LCL
SPDATA	000452	149	RO,D,CON,LCL
SIDATA	000012	5	RW,D,CON,LCL
SVARS	000442	145	RW,D,CON,LCL
STEMPS	000002	1	RW,D,CON,LCL
FCTB	000100	32	RW,D,OVR,GBL
.$$$$.	006724	1770	RW,D,OVR,GBL,SAV

TOTAL SPACE ALLOCATED = 011556 2487

F77 -- 1 ERRORS MINES.FTN;343

'TRAISE' -

A PROGRAM FOR CALCULATION OF

TIME DEPENDENT VARIATION

IN RADON, THORON AND DAUGHTER CONCENTRATIONS

AT THE HEAD OF A PILOT RAISE

Prepared by A.G. Scott

April 1984

INTRODUCTION

The concentrations of radon thoron and daughters at the head of a raise are set by the release rates of radon and thoron from the surfaces, the quality and quantity of the ventilation air supplied, and the volume that is effectively ventilated.

When raises are driven with compressed air as the only source of ventilation air, the quantity of air supplied varies with the phases of the mining cycle, and consequently, the concentrations change from phase to phase. A time dependent computer model is required to simulate these variations.

PROGRAM DESCRIPTION

General

Air released at the end of a raise either from a drill or from a compressed air hose has velocity and momentum, and will travel some distance before that velocity is dissipated. As a result, the air at the end of a raise is well mixed,with circulation velocities much higher than the bulk velocity of the air down the tunnel. If the tunnel is ventilated by cracking open the compressed air line, the mixing zone extends from the air release point to the face, if the drill is the only source of air, the mixing zone extends about 2 tunnel diameters from the face.

The air the miner breaths for most of his work cycle is the air in this mixing zone, not the air in the rest of the tunnel. As the amount of compressed air released varies from nil during scaling to 8 m^3/min when drilling, a local time dependent model is needed to estimate the

concentrations that might be met with at different stages in the mining cycle.

The computer program solves this case when the tunnel dimensions, length of the mixing zone, and supply rates of radon, thoron, and ventilation air are known. A Runge-Kutta routine is used to solve the differential equations for the production and removal of radon, thoron, and their daughters in a ventilated mixing zone. The equations and Runge-Kutta solution routine are the same as those discussed in detail in the program 'MINES'.

To use the program, the mining cycle is divided into time segments over which the release and removal parameters of radon and thoron and their daughters, and the release of particulates is essentially constant. These values are specified, together with the duration of the time segment and the intervals at which concentration estimates will be calculated. Initial values of concentration can be entered for the first time segment only; all subsequent concentrations are calculated from the supply and removal rates.

The data for each segment is entered into the computer, either from a terminal or from a card reader, echo checked, and printed. The change of concentrations with time in each segment are then printed in chronological order.

FLOW CHART

A flow chart for the program is shown in Figure 1. A program listing is provided.

Data Entry

The program will accept data from either a terminal or a card reader. The data required is prompted from the terminal. An example of a data entry session is shown in Figure 1. The data entered is echoed back, together with calculated values of input and removal rates on a unit volume basis as shown in Figure 2.

Presentation of Results

The changes in radionuclide concentrations over the time segment are calculated, and listed at the selected time intervals over the segment. A listing is generated for each time segment as shown in Figure 3.

TECHNICAL DETAILS

Subroutine Set

A number of parameters change from time segment to time segment, and the final radionuclide concentrations of one segment are the initial concentrations of the next. Subroutine 'set' copies the values needed from the storage array into the dummy variables needed for the computation routines.

Subroutine RKGS

This solves the simultaneous differential equations given in subroutine FCT for the changes in concentration of radon, thoron and their daughters produced by changes in radon and thoron supply rates, attachment rates and removal rates. A modified IBM scientific subroutine is used, in which the time step over which the equations are evaluated is automatically modified to obtain a given level of accuracy. This routine is the same as that used in 'MINES'.

Subroutine Output

This prints the calculated concentrations in the mixing zone for each time segment and in chronological order.

```
     ENTER IDENTIFIER
EXAMPLE
       READ FROM CARDSTY

  ENTER WORKPLACE LNGTH,X-SECT.,PERIM.,TYPE
     10.0         4.5         9.0M

    ENTER INITIAL RADON/THORON CONCS.

  ENTER RN,RAF,RAA,RBF,RBA,RACF,RACA(PCI/LITRE)
   2000.000000000000          0.0000000000000000          0.0000000000000000
  0.0000000000000000          0.0000000000000000          0.0000000000000000
  0.0000000000000000

  ENTER ATTACHMENT RATE (/MIN)
   50.00000000000000

  ENTER TN,THBF,THBA,THCF,THCA(PCI/LITRE)
   150.0000000000000          0.0000000000000000          0.0000000000000000
  0.0000000000000000          0.0000000000000000
LAST
     ENTER TIME STEP (MIN)
                              1.000000000000000

  ENTER DURATION OF PHASE (MIN)
   15.00000000000000


  ENTER RADON,THORON,SUPPLY RATE(PCI/M2/MIN)
   910.0000000000000          9000.000000000000

  ENTER TOTAL INCREASE IN ATTACH. RATE(/MIN)
  0.0000000000000000

  ENTER DEPOSITION VELOCITIES VF,VA (M/MIN)
  0.6000000000000000          3.0000000000000000E-03

  VENTILATION  AIR CONDITIONS


  ENTER AIR QUANTITY(M3/MIN)
   20.00000000000000

  ENTER RN,RAF,RAA,RBF,RBA,RACF,RACA(PCI/LITRE)
   30.00000000000000          1.500000000000000          24.00000000000000
  0.5000000000000000          13.00000000000000          0.0000000000000000
   10.00000000000000

  ENTER ATTACHMENT RATE (/MIN)
   3.000000000000000

  ENTER TN,THBF,THBA,THCF,THCA(PCI/LITRE)
   3.000000000000000          0.0000000000000000          1.000000000000000
  0.0000000000000000          0.3000000000000000

 ENTER DRILL AIR VOLUME(M3/MIN),ATMNT RATE(/MIN)
  0.0000000000000000          0.0000000000000000

    ALL DONE
```

FIGURE 1

```
                    EXAMPLE
                              BLAST


              WORKPLACE LENGTH      10.0M              X-AREA       4.5M2       PERIMETER       9.0M

          VENT VOLUME  20.00 M3/MIN     RADON RELEASE RATE   910.0  PCI/M2/MIN  THORON RELEASE RATE  9000.0  PCI/M2/MIN

INCREASE IN ATTACHMENT     0.000            DEPOSITION VELOCITIES,FREE=     0.6004/MIN,   ATTACHED=     0.0034/MIN

                INITIAL CONDITIONS
  RADON      RA-A(F)   RA-A(A)   RA-B(F)   RA-B(A)   RA-C(F)   RA-C(A)
 2000.000     0.000     0.000     0.000     0.000     0.000     0.000

  THORON     TH-B(F)   TH-B(A)   TH-C(F)   TH-C(A)
  150.000      0.000     0.000     0.000     0.000

          ATTACHMENT RATE 50.00

      VENTILATION AIR PARAMETERS
  RADON      RA-A(F)   RA-A(A)   RA-B(F)   RA-B(A)   RA-C(F)   RA-C(A)
   30.000      1.500    24.000     0.500    13.000     0.000    10.000

  THORON     TH-B(F)   TH-B(A)   TH-C(F)   TH-C(A)
    3.000      0.000     1.000     0.000     0.300

          ATTACHMENT RATE  3.00

      TOTAL SUPPLY RATES  RADON=  13.33   THORON=   1.33 PCI/MIN,M3

          DRILL AIR VOLUME  0.00M3/MIN        ATACHMENT RATE  0.00(/MIN)

      TOTAL SUPPLY RATES  RADON=   1.82   THORON=  18.00 PCI/MIN,M3
      REMOVAL RATES FREE=1.20000 ATTACHED=0.00600  ATTACHMENT RATE=   3.00   PER MINUTE
                              RATE OF INCREASE IN ATTACHMENT = 0.00000 (/MIN,M3)
      AIR VELOCITY  4.444 METERS/MIN
                  START TIME=    0.00MIN    FINISH TIME   15.00MIN   TIME STEP=    1.00
```

FIGURE 2

EXAMPLE

BLAST

TIME	RADON	RAA-F	RAA-A	RAA-T	RAB-T	RAC-T	WL-RN	THORON	THB-F	THB-A	THB-T	THC-T	WL-TN	F	KD
0.	2000.0	0.00	0.00	0.00	0.00	0.00	0.00	150.00	0.00	0.00	0.00	0.00	0.00	.000	50.00
1.	1294.4	8.47	253.25	261.72	8.16	3.64	0.32	56.07	0.00	0.43	0.43	0.11	0.05	.025	32.94
2.	842.1	8.03	295.23	303.26	15.68	6.11	0.41	27.99	0.00	0.67	0.67	0.19	0.08	.049	22.07
3.	552.1	7.44	258.64	266.09	20.10	7.79	0.41	19.59	0.00	0.80	0.80	0.24	0.10	.073	15.14
4.	366.2	6.72	203.42	210.14	21.75	8.90	0.36	17.08	0.00	0.88	0.88	0.27	0.11	.098	10.72
5.	247.0	5.89	152.38	158.27	21.64	9.60	0.31	16.33	0.00	0.93	0.93	0.29	0.12	.125	7.91
6.	170.6	5.04	112.15	117.19	20.64	10.02	0.26	16.11	0.00	0.96	0.96	0.31	0.12	.154	5.11
7.	121.6	4.24	82.87	87.11	19.32	10.24	0.23	16.04	0.00	0.98	0.98	0.32	0.12	.186	4.97
8.	90.2	3.56	62.56	66.12	18.02	10.34	0.20	16.02	0.00	0.99	0.99	0.32	0.13	.220	4.24
9.	70.1	3.02	48.89	51.90	16.90	10.37	0.18	16.01	0.00	1.00	1.00	0.33	0.13	.254	3.78
10.	57.1	2.61	39.86	42.47	15.99	10.35	0.16	16.01	0.00	1.00	1.01	0.33	0.13	.286	3.48
11.	48.9	2.32	33.98	36.30	15.30	10.32	0.15	16.01	0.00	1.01	1.01	0.33	0.13	.314	3.29
12.	43.6	2.13	30.17	32.29	14.78	10.29	0.15	16.01	0.00	1.01	1.01	0.33	0.13	.336	3.17
13.	40.2	1.99	27.72	29.71	14.40	10.26	0.14	16.01	0.00	1.01	1.01	0.33	0.13	.353	3.09
14.	38.0	1.90	26.15	28.05	14.14	10.23	0.14	16.01	0.00	1.01	1.01	0.33	0.13	.365	3.05
15.	36.6	1.85	25.14	26.98	13.95	10.20	0.14	16.01	0.00	1.01	1.01	0.33	0.13	.373	3.01

FIGURE 3

APPENDIX 3

EQUIPMENT CALIBRATION

EQUIPMENT CALIBRATION

All radon/radon daughter measurement equipment used in this study was calibrated or checked at the CANMET Laboratory at Elliot Lake. All scalers were checked with a ^{241}Am spectroscopy grade source and a ThB-C filter source, and found to have plateaus long enough that both the 5.5 MeV alpha from ^{241}Am and 8.8 MeV alpha from ThC could be counted with almost the same efficienty at one voltage setting.

Four of the units (3 EDA RD-200A, 1 Eberline SAC-R5 detector, MS3 scaler) used scintillator adaptors to count filters. The average counting efficiency for the adaptors measured with a calibrated ^{241}Am source with the same active area as a filter (AECB Elliot Lake) was 46.5 (SD=0.8)%. One unit (Nurad NR1 used a fixed scintillator. The counting efficiency measured by a calibrated ^{241}Am source with the same active area as a filter was 47.5 (SD=0.5)%.

A nominal counting efficiency of 47% was adopted for all units.

Scintillation cells were calibrated by drawing samples from a large room with a radon concentration of 2000 (SD=100) pCi/L measured with 4 calibrated CANMET cells. The calibration factor for the 15 cells used was 0.7 (SD=0.05) cpm per pCi/L including systematic uncertainties.

The rotameters on the portable pumps used to collect airborne daughters on filter papers were calibrated by bubble tubes by the AECB, Elliot Lake. The filters used were Millipore or Gelman 0.8 μ membrane filters.

The sampling procedure and the scaler calibration and check procedure were those suggested by the AECB in Regulatory Guide R-4 (AE 81).

CONCENTRATION ESTIMATES

Radon and thoron daughter concentrations were estimated from multiple counts on the same filter, which was analyzed by an adaptive least squares fitting program based on Rabbe & Wrenn (Health Phys. 1969, p.593).

This program does not require a fixed sample time or counts to be made at specific times after the sample. The nominal counting regime consisted of 5 minute counts at 1, 6, 45 minutes after the end of the sample,

and 20 minute counts at 2, 4, 16 hours after the sample in an attempt to measure ThC in addition to ThB. All filters received at least the first 3 counts.

If the value of a nuclide is negative, or differs from zero by less than its standard error, the data is automatically re-analyzed on the basis that the nuclide is not present. If there are suitable counts in the 40-90 minute period or 450 to 2000 minute period, the program provides Kusnetz estimates of radon or thoron WL, in addition to the values calculated from the individual nuclide concentrations. The Kusnetz factor for radon daughters was calculated using the equations of Regulatory Guide R-4.

APPENDIX 4

SOLUBILITY OF AIRBORNE DUST IN SIMULATED LUNG FLUID

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SOLUBILITY OF AIRBORNE DUST IN SIMULATED LUNG FLUID

Airborne 'respirable' dust samples from approximately 5 m^3 of air in the vicinity of the miner, and airborne 'total' dust samples from approximately 10^3 of air at the slusher bench were sent to CRNL for analysis. In all there were 12 cassettes of respirable dust and 22 cassettes of total dust.

The total mass of dust removed from all filters by gentle mechanical scraping amounted to 12 mg. The total alpha activity of this dust was estimated at 36 dpm by alpha counting a small fraction.

The dust was put into 350 cm^3 of simulated lung fluid (SLF) as described in Health Physics 46, 151 (1984), and shaken continuously. Each day the container was centrifuged, and 300 ml of fluid taken off, and replaced by 300 ml of fresh SLF.

The removed SLF from selected days was analyzed for Th, U, and Ra by chemical separation followed by alpha spectroscopic counting. The results were:

Day	Activity Dissolved (dpm)/day		
	Th	U	Ra
1	0.36	5.3	*
2	-	-	0.1
3	1.6	2.0	*
10	0	0	*
30	0	0.1	0.0

* No result due to contaminated reagents.

Comments

The collected dust contained an unknown fraction of non-radioactive material from diesel exhaust, blasting fumes, and drill lubricating oil

droplets. The specific activity of 3000 dpm/g was about 25% of that expected from ore dust, suggesting that only 3 mg of ore were collected in total.

Although the low activity makes definitive statements impossible, it appears that there is a soluble uranium component in the dust with a dissolution half life in the region of 3 days. As much as 10 dpm of uranium may have been dissolved by the lung fluid.

The activity of thorium in the ore is about 25% of the uranium activity, and the dissolved thorium activity is also about 25% of the dissolved uranium. This suggests that the soluble fractions of both thorium and uranium may be equal, although the dissolution rates may differ. Reagent contamination prevented accurate radium measurements, but the measurement at day 2 suggests that the radium is not more soluble than uranium.

Approximately 35% of the airborne radioactive dust collected had a dissolution half life in the region of 3 days (Class D), and the remainder has a much longer period (Class W).

APPENDIX 5

VENTILATION MEASUREMENTS

Ventilation rates were estimated by measuring the change of concentration with time (clearance rate) of sulphur hexafluoride (SF_6) tracer gas released in the space. Air samples were collected in evacuated glass tubes, and analyzed subsequently by gas chromatography. Evacuated glass tubes closed with a rubber stopper incorporating a septum are sold as 'blood collection tubes'. The septum will reseal airtight after it has been pierced by a hypodermic needle.

SF_6 gas was withdrawn from a pressurized storage cylinder through a septum by a 3 ml hypodermic syringe and injected into a 5 ml evacuated tube through the stopper septum to produce a 'source tube'. The gas was released at a known time into a space by removing the rubber stopper or smashing the tube.

Air samples are taken at a known time after the release by removing and then replacing the stopper from a 10 ml evacuated tube. The tubes have blank labels attached, so location and sample time are recorded directly on the tube.

For the studies mentioned here, air samples were taken at intervals of a few minutes over periods of 10 to 30 minutes. Samples can be stored in the tubes without significant loss for several months.

The concentration of SF_6 in the tube air was measured later at the surface by withdrawing a 1 cm^3 sample from the tube with a 1 cm^3 hypodermic syringe inserted through the stopper septum. The contents of the syringe were injected into a gas chromatograph (loaned by the Ontario Ministry of Labour), and the SF_6 concentration estimated from the height of the SF_6 peak registered on a chart recorder. A concentration of as low as 10 ppb SF_6 can be measured. In an enclosed space with good air mixing and a constant ventilation rate, the decrease of concentration with time is exponential, and the supply of a volume of air equal to the space volume will reduce the concentration to 1/e of the initial value. The logarithms of the measured concentrations are plotted against time, and a straight line fitted. The time required to reduce concentration to 1/e of the initial value is the ventilation period (units = minutes per air change), and is read directly from the graph. The ventilation rate (unit = air changes/minute) is the inverse of ventilation period.

In large spaces, the decrease of concentration with time at a location is not always exponential. There is often a rapid initial drop as the gas is cleared from the release area, followed by a slower decrease after recirculation currents have mixed the gas into the entire volume. In this case, 'clearance period' is determined from the initial stope of the graph.

APPENDIX 6

DUST EXPOSURE AND VENTILATION RATE

DUST EXPOSURE AND VENTILATION RATE

THEORY

Let dust particles be released at rate S s^{-1} with good mixing for a time T into a volume Qm^3 ventilated at V m^3/s. If we put V/Q = R, the removal rate by ventilation, then the dust concentration in the space at time t is given by C, where

$$C = \frac{S}{V}(1 - e^{-Rt}) \text{ p/m}^3$$

The exposure to dust in the space = $\int_0^T C dt$

$$= \frac{S}{V}\left(T - \frac{(1 - e^{-RT})}{R}\right) \text{ p.s.}$$

After the end of the release, the concentration will be given by

$C = C_T e^{-R_2 t}$, where R_2 is the ventilation rate after the release.

The exposure = $\int_0^\infty C dt = \frac{C_T}{R_2}$ p.s.

$$= \frac{S}{VR_2}(1 - e^{-RT}) \text{ p.s./m}^3$$

The total exposure E during release and clearance is therefore

$$E = \frac{ST}{V} - \frac{S}{VR}(1 - e^{-RT}) + \frac{S}{VR_2}(1 - e^{-RT}) \text{ p.s./m}^3$$

If $R = R_2$, then

$$E = \frac{ST}{V} \text{ or } \frac{ST}{QR} \text{ p.s./m}^3$$

If the same amount of dust is released (ST = constant), the difference in exposures caused by differences in ventilation rate and ventilated volume are simply in the inverse ratios of the product of their product.

For example, when auxiliary ventilation was in use, the measured ventilation period was 1 minute - a removal rate of 0.017 s^{-1}, and the length of circulation zone (= ventilated volume) was 8 m. When the drill air was the sole source of ventilation air, the ventilation period was about 10 minutes - a removal rate of 0.0017 s^{-1}, and the length of the circulation zone was about 5 m. For the same dust release, the nominal ratio of the exposures would be 1:16. In practice, the amount of air released per minute during collaring is less than during drilling, so the total exposure will be higher. The ventilation period during collaring is estimated at 20% longer or 12 minutes, which would increase the nominal exposure ratio to 1:20.

APPENDIX 7

RADON AND THORON EXHALATION

RADON AND THORON EXHALATION

The steady state solution of the 1 dimensional diffusion equation gives the atom flux rate J from the surface of a semi-infinite material of a radioactive gas as

$$J = \; \updownarrow (\frac{D}{\lambda})^{\frac{1}{2}} \text{ atom/m}^2\text{/s}$$

where $\updownarrow$ = atom production rate per unit volume
D = diffusion coefficient
λ = radioactive decay constant

Both radon and thoron atoms have similar atomic weights, and so their diffusion coefficients will be similar. If the atom production rates of radon and thoron are equal, then their atom fluxes will be in the ratio

$$\frac{J_R}{J_T} = \frac{\updownarrow (D/\lambda_R)^{\frac{1}{2}}}{\updownarrow (D/\lambda_T)^{\frac{1}{2}}} = (\frac{\lambda_T}{\lambda_R})^{\frac{1}{2}}$$

$\lambda_R = 2.1 \times 10^{-6}\ s^{-1}$, $\lambda_T = 0.0132\ s^{-1}$, so $J_R/J_T = 80{:}1$ on an atom basis. On an activity basis, the fluxes will be 80 λ_R/λ_T, or 1:80.

If the active material is covered by a thin layer of inactive material, the flux rates will be reduced. The exact solution is complicated, but an approximation is $J < J_0\, e^{-X/L}$,

where X is the thickness and $L = (\frac{D}{\lambda})^{\frac{1}{2}}$

The diffusion coefficient of radon or thoron in water is 1×10^{-5} cm^2/s, so L for radon in water is 2.2 cm, and for thoron is 0.027 cm. A thin water film of 0.06 cm thickness on an active surface will reduce the thoron atom flux by a factor of 10, but only reduce the radon flux by 3%. The activity flux ratio of 1:80 only applies to dry surfaces. The ratio for wetted surfaces will be lower, by an amount dependent on the effective water film thickness.

APPENDIX 8

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